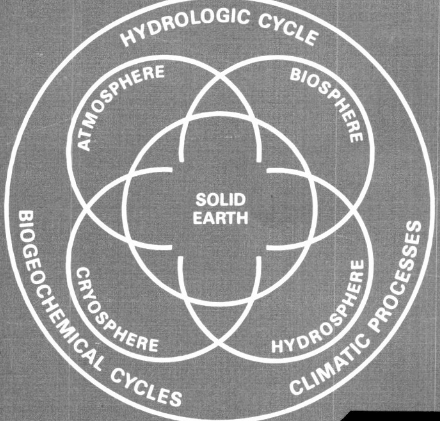
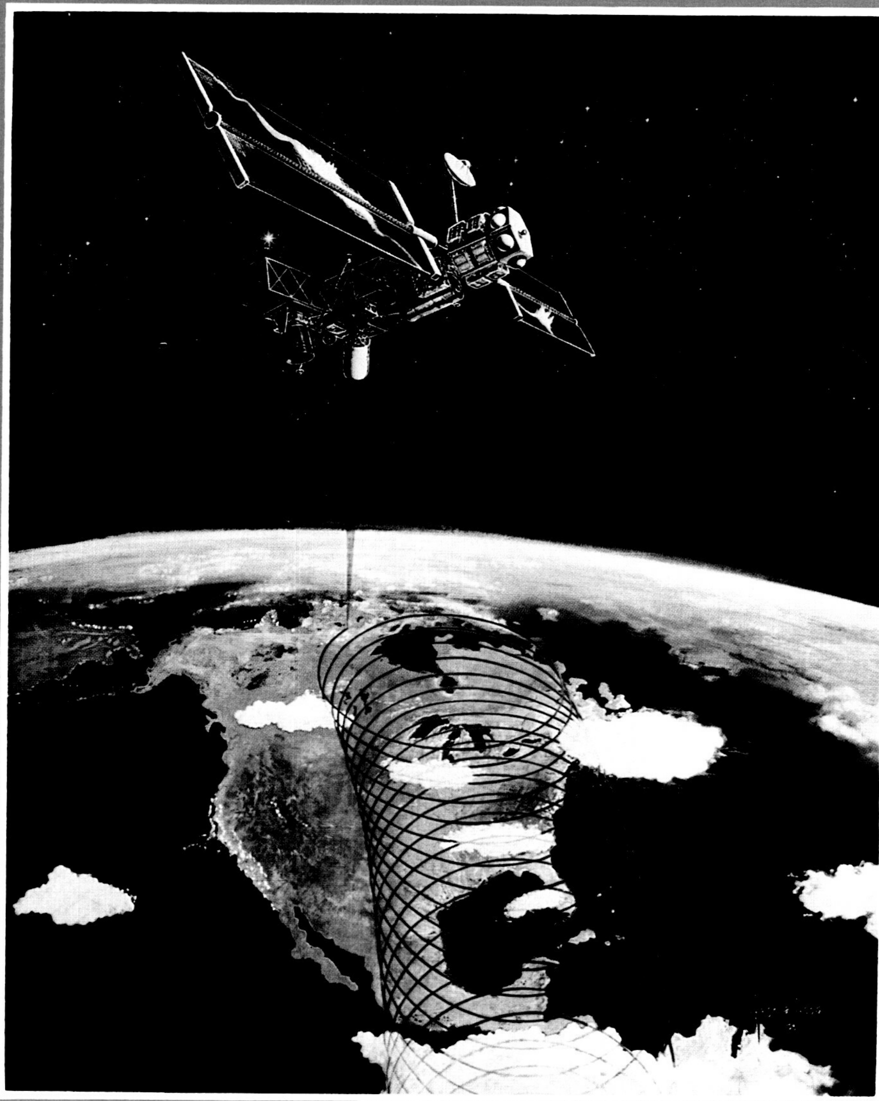


Volume IIg

LAWS

Laser Atmospheric Wind Sounder

EARTH OBSERVING SYSTEM



INSTRUMENT PANEL REPORT

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LAWS
Laser Atmospheric Wind Sounder

EARTH OBSERVING SYSTEM
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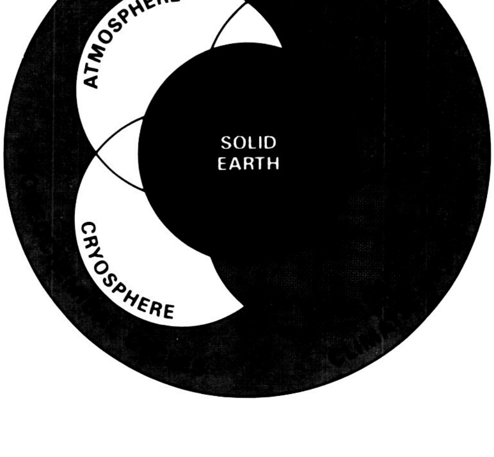

INSTRUMENT PANEL REPORT

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EARTH OBSERVING SYSTEM REPORTS

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Volume IIa	Data and Information System Data Panel Report
Volume IIb	MODIS Moderate-Resolution Imaging Spectrometer Instrument Panel Report
Volume IIc	HIRIS High-Resolution Imaging Spectrometer: Science Opportunities for the 1990s Instrument Panel Report
Volume IId	LASA Lidar Atmospheric Sounder and Altimeter Instrument Panel Report
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LASER ATMOSPHERIC WIND SOUNDER PANEL FOR THE EARTH OBSERVING SYSTEM

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PREFACE

The Laser Atmospheric Wind Sounder (LAWS) Panel was organized to develop the scientific objectives and corresponding engineering requirements for a spaceborne Doppler laser wind sounder as part of NASA's Earth Observing System (Eos) study. The initial concept of LAWS was described in Volume I of the Earth Observing System Report (Butler *et al.*, 1984). Panel members were selected by the Earth Science and Applications Division of NASA Headquarters.

As will be seen in the body of this report, the Panel found that the LAWS instrument was feasible for a mid-90s launch into low-Earth orbit on an Eos platform and that it would make a strong scientific contribution to our understanding of the Earth as an integrated system. LAWS wind profiles would provide key insights into a wide range of interdisciplinary science areas such as the hydrologic and biogeochemical cycles and the interrelated climatic processes where winds play a more obvious role.

The LAWS Panel accomplished its task through a series of panel meetings held over a period of 8 months. The necessary simulation calculations and report writing were performed by the Panel members at their respective institutions. (Panel members came from both U.S. and international organizations.)

Meeting logistics, as well as the difficult job of document preparation, were most ably handled by Ms. Lori Nelson and Ms. Terry Edgar of Birch & Davis Associates, Inc., Silver Spring, Maryland. It is a pleasure to acknowledge their support and that of other staff members at Birch & Davis Associates, Inc.

Recording of the proceedings of the Panel meetings and final technical editing of this report were performed by Mr. Reynold Greenstone of ORI, Inc., Rockville, Maryland. The Panel wishes to acknowledge the strongly professional efforts of Mr. Greenstone, without whose efforts this report would be considerably less well organized.

Although brief mention is given in the text, the quality and scope of this document were greatly enhanced by the contributions of two of the Panel members affiliated with the U.S. Air Force. Dr. Kenneth Hardy of the Air Force Geophysics Laboratory reviewed the wind sensing requirements for the research and operational activities of his organization. Lt. Sylvia Ferry of the Air Force Defense Meteorological Satellite Systems informed the Panel of her organization's plans for development of a satellite wind sensing instrument. Since the instrument objectives of the NASA and Air Force development programs are quite similar, continued interaction between these two programs offers the potential for accelerated progress.

A number of individuals aided in discussions with the Panel to develop the science concepts for the application of LAWS in Eos. Martin Donohoe provided details of the instrument complement anticipated for the polar platform. The science requirements for LAWS were developed through a series of discussions strongly influenced by Drs. Robert Atlas, George Fichtl, Eugenia Kalnay, and Ronald McPherson. In addition, instrument concepts were greatly aided by discussions with Drs. Freeman Hall and George Wood. The strength of this document is a reflection of the contributions of all of these individuals.

Robert J. Curran
Chairman, LAWS Instrument Panel
National Aeronautics and Space Administration, Headquarters
Washington, D.C.
January 1987

EXECUTIVE SUMMARY

It is possible to measure wind profiles from space using current technology. These wind profiles are essential for investigating many of the interdisciplinary scientific questions to be addressed by Eos, the Earth Observing System. The purpose of this report is to provide guidance for the development of a spaceborne wind sounder, the Laser Atmospheric Wind Sounder (LAWS), by discussing the current state of the technology along with its heritage and by reviewing the scientific rationale for the instrument. Whether obtained globally from the Eos polar platform or in the tropics and subtropics from the Space Station, wind profiles from space will provide essential information for advancing the skill of numerical weather prediction (NWP), furthering our knowledge of the large-scale atmospheric circulation and climate dynamics, and improving our understanding of the global biogeochemical and hydrologic cycles. Eos will provide the ideal platform for this new instrument, and the LAWS Instrument Panel recommends that it be given high priority for new instrument development because of the pressing scientific need and the availability of the necessary technology.

The requirements, which can be met by LAWS, are to measure wind profiles with an accuracy of a few meters per second and to provide samples at intervals of about 100 km horizontally for layers 1 km thick.

SCIENCE OBJECTIVES

Numerical Weather Prediction

The experience of operational weather prediction centers and considerable recent research has indicated that wind profiles are the single most important new data source because they have the potential to effect dramatic improvement in NWP. This improvement will occur through the enhancement of the coverage and data quality in areas already served by conventional radiosondes, and through the extension of the coverage of high-quality wind profiles to the sparsely instrumented oceanic and southern hemisphere areas. Simulation experiments indicate that weather forecasts would improve to the point that the southern hemisphere weather could be predicted with as much skill as the northern hemisphere. Moreover, even in the much better observed northern hemisphere, specific cases of very significant forecast improvement have been noted using simulated wind profile data.

In the tropics, wind observations are even more important than in mid-latitudes, since pressure patterns cannot be used to calculate atmospheric motion, and there are few observing stations. The tropics are of particular interest because much of the global energy input to the atmosphere occurs there, and because there are teleconnections between large-scale atmospheric phenomena in the mid-latitudes and anomalies in the tropics as evidenced in the recent El Niño episode.

Understanding Mesoscale Systems

A number of research and operational mesoscale phenomena can be investigated using the high-density wind profiles provided by the LAWS instrument.

Climate Dynamics

The analysis of long-term atmospheric behavior may depend critically on details of the wind field at points around the globe. The regions of energy input to the atmosphere are most important for climate prediction so that the tropics become of special interest, but a global perspective is imperative for climate analysis.

Biogeochemical and Hydrologic Cycles

Obtaining a better understanding of the atmosphere, oceans, cryosphere, and biota as a coupled system is the essence of the Eos concept. Atmospheric dynamics plays a central role in coupling the elements of the entire system through the transport of heat, water vapor, momentum, and trace gases. Wind observations and models are needed to provide a better definition of the hydrologic cycle and the long-range transport of trace gases and aerosols.

TECHNOLOGY OF SPACEBORNE WIND MEASUREMENT

Simulations and field experiments have shown that, to make a significant improvement in weather and climate modeling over present capabilities, a space-based wind measurement program must: (1) increase beyond present coverage; (2) sample at intervals of about 100 km horizontal by 1 km vertical; (3) measure with an accuracy of a few meters per second; and (4) provide wind *profiles* rather than single-level data. A number of different laser system configurations exist for this application, which include use of either gas dynamic lasers (CO_2, excimer) or solid-state lasers with either coherent or incoherent detection approaches. These candidate technologies are under study to assess their suitability to make effective wind measurements from a satellite. The system technology which has been used for a number of years to remotely sense winds, and therefore has the longest heritage, is the coherent CO_2 Doppler lidar. This system, operating in the eye-safe infrared wavelength range (9 μm to 10 μm), has been used in ground-based and airborne applications, and has been used successfully for a variety of research purposes. Satellite and shuttle design studies have been undertaken and have indicated that the technology can be developed economically for spaceborne use. Although the coherent CO_2 laser system approach is considered most suitable at the present time for this application, technology advances in the next several years may prove other system approaches to be more feasible. As an active instrument, a Doppler lidar will have relatively large power requirements which can best be met with the Eos polar-orbiting platform or the manned Space Station (if one sacrifices global coverage for intense tropical sampling).

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ACRONYMS AND ABBREVIATIONS

AFGL	Air Force Geophysics Laboratory
ANSI	American National Standards Institute
atm.	Atmosphere
CAS	Computed Airspeed
CAT	Clear Air Turbulence
CNES	Centre National d'Etudes Spatiales
CNRS	Centre National de la Recherche Scientifique
CTW	Cloud-Track Wind
cw	Continuous Wave
DFVLR	German Aerospace Research Establishment (Deutsche Forschungs-Und Versuchsanstalt Fuer Luft-Und Raumfahrt)
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium Range Weather Forecasts
ESA	European Space Agency
FFT	Fast Fourier Transform
FGGE	First GARP Global Experiment
FSR	Free Spectral Range
GARP	Global Atmospheric Research Program
GCM	General Circulation Model
GEC	General Electric Corporation
GFDL	Geophysical Fluid Dynamics Laboratory
GLA	Goddard Laboratory for Atmospheres
GLOBE	Global Backscatter Experiment
GSS	Gain Switched Spike
GWM	Global Wind Measurements
HMMR	High-Resolution Multifrequency Microwave Radiometer
HRDI	High-Resolution Doppler Interferometer
HRE	High-Resolution Etalon
IPD	Image Plane Detector
JAWS	Joint Airport Weather Studies
JFK	John F. Kennedy Airport
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
LASA	Lidar Atmospheric Sounder and Altimeter
LAWS	Laser Atmospheric Wind Sounder
LMSC	Lockheed Missiles and Space Corporation
MCS	Mesoscale Convective System
MEOSS	Monocular Electro-Optical Stereo Scanner
MOPA	Master Oscillator Power Amplifier
MSFC	Marshall Space Flight Center
NIES	National Institute for Environmental Studies
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OSSE	Observing System Simulation Experiment

ACRONYMS AND ABBREVIATIONS (continued)

PPI	Plan-Position Indicator
PRF	Pulse Repetition Frequency
RAE	Royal Aircraft Establishment
RHI	Range-Height Indicator
rms	Root Mean Square
RSRE	Royal Signals and Radar Establishment
SAGE II	Stratospheric Aerosol and Gas Experiment II
SAW	Surface Acoustic Wave
SCALE	Shuttle Coherent Atmospheric Lidar Experiment
SEAREX	Sea Air Exchange Experiment
SLM	Single Longitudinal Mode
SOP-1	First Special Observing Period
SROSS-2	Stretched Rohini Satellite Series
STORM	The National Storm Scale Operational and Research Meteorology Program
TAS	True Airspeed
TEA	Transversely Excited Atmospheric Laser
TIROS-N	Television Infrared Observation Satellite
TSC	Transportation Systems Center
UARS	Upper Atmosphere Research Satellite
VAD	Velocity Azimuth Display
WPL	Wave Propagation Laboratory

I. INTRODUCTION

An improved understanding of the atmospheric wind field is essential for investigating many of the interdisciplinary scientific questions which may ideally be pursued from a polar orbiting platform of Eos, the Earth Observing System. Consequently, the Laser Atmospheric Wind Sounder (LAWS) is a significant component of the Eos instrument complement.

Wind profiles obtained by the LAWS system will provide research information essential for advancing the skill of numerical weather prediction (NWP), furthering our knowledge of large-scale atmospheric circulation and climate dynamics, and improving our understanding of global biogeochemical and hydrologic cycles. The special importance of global wind vector fields in *operational* numerical weather analysis and prediction systems demonstrates the need for an accelerated program for development of a spaceborne sensor for profiles of atmospheric winds. The increased use of global wind vector fields in numerical prediction models offers perhaps the greatest potential for increased accuracy in operational forecasts (Appendices A and B). More, and more-detailed temperature soundings are held to be of less importance, especially in low-latitude regions.

In addition to providing essential initial data for NWP, the global wind data set obtainable from the LAWS system will form a significant component of the temporally continuous global data base required for studies of the coupled climate system. This data base is needed to: (1) describe the atmospheric general circulation including annual cycles and interannual changes and the transport of energy, momentum, moisture, trace gases, and aerosols in the atmosphere; (2) quantify the cycles of atmospheric variables that are key ingredients of climate change; (3) test and verify existing climate models and develop new and improved ones; and (4) advance theories of climate and its variations.

It is possible, using current technology, to obtain the required wind data for these multidisciplinary topics by measuring global wind profiles from space. The instruments necessary to make the measurements have progressed through a steady evolution from small, experimental units probing dust devils, through complex airborne scanners yielding mesoscale winds, to instruments with the power required to make measurements from space. Eos provides an opportunity to make the goal of obtaining global wind measurements a reality.

We have concluded that at the present time, the coherent Doppler lidar is the only instrument with the measurement heritage and technological readiness required for consideration of space-based operation. This system consists of a pulsed, frequency-controlled, CO_2 laser transmitter, a continuously scanning transmit-and-receive telescope, a heterodyne detector, and a signal processing system. Operation of the lidar is shown in Figure 1. A laser pulse is directed through the telescope to the atmosphere, and a small fraction of the incident radiation is backscattered by naturally entrained aerosols. This radiation is collected by the same telescope that was used to transmit the laser pulse and combined with radiation from a local oscillator for heterodyne detection. Since the aerosols are moving relative to the transmitter, the backscattered radiation is Doppler shifted from the transmitted frequency by an amount proportional to the line-of-sight component of the aerosol relative

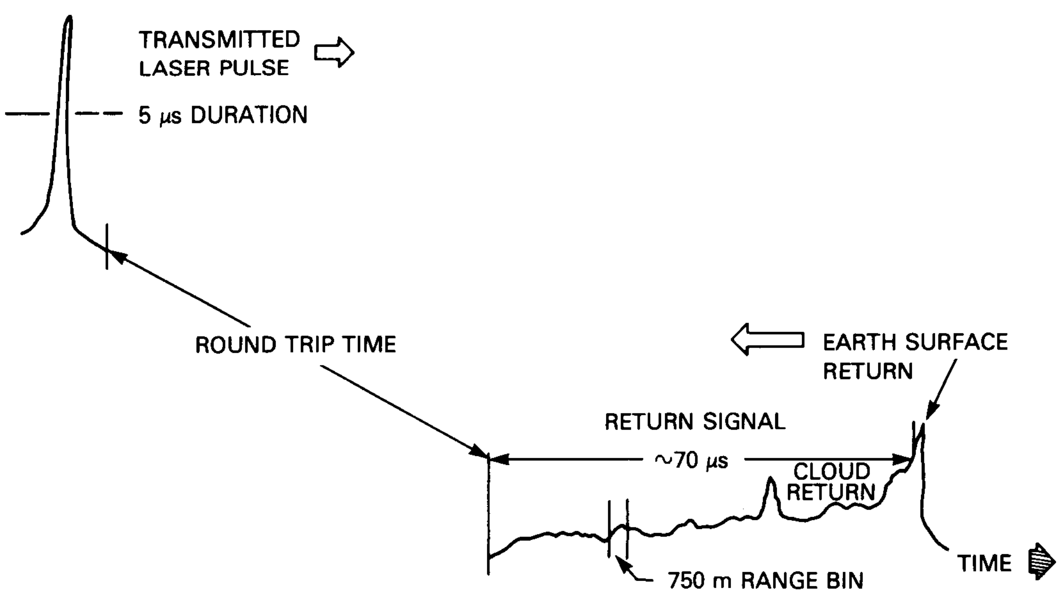


Figure 1. Depiction of transmitted laser pulse and backscattered radiation.

velocity, from which the air motion may be found by removing the spacecraft motion. Heterodyne detection of this radiation results in a detector output in the form of a frequency modulated wave whose modulation frequency is the difference between the transmitted and received frequencies, i.e., the Doppler shift imparted by the air motion.

Since the process inherently measures only the *line-of-sight* velocity component, scan techniques and processing algorithms must be employed to obtain the desired horizontal wind vectors. The combination of telescope scanning and spacecraft motion allows the same atmospheric volume to be seen from different look angles. These line-of-sight measurements are then weighted, taking into consideration such parameters as signal-to-noise, proximity, and line-of-sight angle. The weighted values are then combined to produce a vector velocity for that particular volume of atmosphere. The ability to perform these measurements is in large part determined by the transmitted energy and the amount of aerosols present in the atmosphere. Two key research programs associated with this LAWS effort are designed to examine the global extent of aerosol distribution and to assess the various candidate laser configurations as to their ability to meet transmitter performance requirements at the required energy level.

In this volume we describe the science requirements, instrument definition, and data management system necessary to achieve an Eos global wind measurement system. Specifically, Chapter II contains the science requirements. The atmospheric modeling studies which would be advanced by the additional wind data are discussed in Chapter III.

A comparison of various wind measurement techniques is presented in Chapter IV, and the heritage of the Doppler lidar instrument is contained in Chapter V. Chapter VI reports on developments in pulsed Doppler lidar transmitter technology, and Chapter VII discusses overall measurement requirements and gives an assessment of our current understanding of atmospheric aerosols. In Chapter VIII, the required data management system is outlined. The concept and strategy for developing a space-based wind profiler are discussed in Chapter IX, and finally, Appendix C presents the results of a hardware definition study for a *Shuttle Coherent Atmospheric Lidar Experiment* (SCALE).

II. SCIENCE OBJECTIVES

Knowledge of the global wind field is widely recognized as fundamental to advancing our understanding and prediction of the total Earth system. Yet, because wind profiles are primarily measured by land-based rawinsondes, the oceanic areas (covering roughly three quarters of the Earth's surface) and many regions of the less-developed southern hemisphere land areas are poorly observed. The gap between our requirements for global wind data and their availability continues to widen. For example, as faster computers become available to model the atmosphere with ever increasing resolution and sophistication, our ability to do so will be hampered because of the lack of data, particularly wind profiles.

In this chapter we discuss the importance of additional wind profiles for improving NWP, understanding and predicting mesoscale systems, and for a wide range of atmospheric diagnostic studies. In addition, the importance of wind information for addressing various multidisciplinary questions involving the global biogeochemical and hydrologic cycles will also be discussed.

IMPROVED NUMERICAL WEATHER PREDICTION

One of the most important applications of wind observations is in the field of numerical weather prediction. Significant progress has been made in this area in the last 10 years, especially with the development of accurate global NWP models, as well as with improved global coverage of the atmosphere provided by satellite observing systems. With the successful completion of the Global Weather Experiment in 1979, operational centers (e.g., the European Centre for Medium Range Weather Forecasts (ECMWF), the National Meteorological Center (NMC), and research laboratories such as the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Laboratory for Atmospheres (GLA)) began producing forecasts that retained some useful skill beyond 5 days, much longer than was possible just a few years before.

However, we are still not close to the 2-week theoretical limit of dynamical predictability. It is clear that further improvements will be necessary in the observations that provide the initial data for the models as well as the objective analysis techniques.

The first NWP models were designed to use only mass (height) data. Winds were derived from the mass observations using the geostrophic relationship. This relationship assumes that the latitudinally dependent Coriolis force is balanced by the pressure gradient force. This was a natural choice because pressure observations were more abundant and more accurate than wind observations. With the advent of global primitive equation models, however, the need for accurate wind profile data has become increasingly clear. There are two independent reasons for this (Kalnay *et al.*, 1985).

The first reason is derived from the concept of geostrophic adjustment (Rossby, 1938; Washington, 1964; Daley, 1980). On the scales measured by a data swath of a low Earth-orbiting satellite, variations in mass data are quickly rejected by the model. This rejection process is consistent with atmospheric behavior. Specifically, small-scale pressure-height variations do not result in small-scale changes in the wind field; instead they are rapidly dispersed as gravity waves. Simply posed, models accept the wind data more readily than mass data for scales which can be observed. Pressure or height data are not retained as well unless they are forced *a priori* to be in geostrophic balance with the winds.

The second reason for the importance of wind data is that integration of noisy observations reduces the effect of random noise, whereas differentiation enhances the effect of noise. The geostrophic relationship implies that wind is proportional to the horizontal pressure gradient; at increasingly smaller scales, the geostrophic relationship is often invalid so that winds become an increasingly more accurate measure of the atmospheric state than pressure or height measurements. Specifically, winds are relatively more accurate than height measurements if $\delta v < (2\pi g/Lf_0)\delta z$, where δv and δz are the wind and height errors respectively, L the horizontal scale, g gravitational acceleration, and f_0 the average value of the Coriolis parameter. As pointed out by Phillips (1983), this relationship indicates that for short scales ($L \sim 2{,}000$ km), satellite winds with a component accuracy of 2.7 m s^{-1} at 500 mb and 5.0 m s^{-1} at 250 mb would bring the combined accuracy of satellite temperatures and winds to the same level globally that the current rawinsonde network has over land in the northern hemisphere. Table 1 gives required rms accuracies of wind components measured from satellites to achieve *analysis* accuracies over the oceans

Table 1. Required Satellite Wind Component Accuracies*

Horizontal Scale L (10^6 m)	Wind Component Error δv (m s^{-1}) 500 mb	250 mb
2	2.7	5.0
4	1.8	3.7
6	1.2	2.8
8	1.0	2.2

*Reproduced from Table 2 of Phillips (1983).

comparable to those obtainable from the current land-based rawinsonde network. The component wind errors should be multiplied by $\sqrt{2}$ to give rms vector wind errors.

In the tropics, wind observations are even more important for numerical weather prediction because the quasi-geostrophic balance present in mid-latitudes does not exist. In addition, the wind field cannot be determined accurately from the height field because the height errors are as large as the horizontal height variations. Moreover, a reliable estimate of the divergent component of the wind is necessary to depict the convective areas in the tropics, which provide a source of energy for not only the equatorial regions but also, at times, the mid-latitudes.

The problem of data assimilation in the tropics is particularly serious because of the lack of measured wind profile data throughout the troposphere. Single-level reports, such as from cloud-track winds, are inadequate to capture the detailed vertical structure of the tropical atmosphere (also a problem in mid-latitudes). This may explain why in some cases tropical wind data which existed during the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) (primarily cloud-track wind data) exerted a negative influence on the extratropical forecasts for the northern hemisphere (Baker and Paegle, 1983; Kalnay *et al.*, 1985). Also, wind profiles are needed to reduce the rapid model error growth in the tropics resulting from deficiencies in parameterizing deep convection.

From the observational requirements discussed above, the following recommendations were established and are contained in the report of the NASA Workshop on Global Wind Measurements (GWM) (1985):

- The coverage of the present global operational observing system for measuring winds should be increased over the oceans and in the tropics and the southern hemisphere.
- The spatial and temporal resolution should be compatible with the resolution of present and future numerical prediction models. A horizontal resolution of about 100 km, vertical resolution of about 1 km (~0.5 km in the boundary layer and in the vicinity of the jet stream), and temporal sampling of at least 6 hours are needed.
- The accuracy of the horizontal wind components should be on the order of 1 to 2 m s^{-1} in the lower troposphere and 2 to 5 m s^{-1} in the upper troposphere in order to make the observing system over the oceans as useful as the rawinsonde network over land.
- Wind profiles rather than single-level data should be measured for use in numerical analysis and forecasting because the profile data can be utilized more effectively. Recent simulation studies [see Chapter III] also indicate that more accurate forecasts would result from using additional wind profiles compared to those obtained with additional single-level winds.

IMPROVED UNDERSTANDING OF MESOSCALE SYSTEMS

Along with the increasing recognition of the importance of having global measurements for successful medium-range (3 to 10 days) and short-range (1 to 2 days) numerical weather forecasts, the importance of obtaining mesoscale and cloud-scale observations for very short-term forecasts (3 to 18 hours) and nowcasts (0 to 3 hours) is also becoming increasingly evident. For example, there is abundant evidence that many of the most significant cool- and warm-season weather events are strongly affected by jet streaks and their associated secondary (vertical) circulations (e.g., Cahir, 1971; Brill *et al.*, 1985). The conventional sounding network has difficulty resolving these mesoscale features, and, as a consequence, the initial conditions for operational numerical models fail to capture important details necessary for a successful forecast. Obtaining the necessary mesoscale information to make such predictions is particularly important in this case since mesoscale convective systems are responsible for much of the severe weather and many flash floods that are now a leading meteorological cause of fatalities and property damage in the United States. On even smaller scales (e.g., cloud-scale circulations), it is now well documented that high-resolution (in both time and space) observations of boundary layer winds are necessary to nowcast the disastrous low-level wind-shear conditions (microbursts) that frequently plague the aviation industry during takeoffs and landings (Roberts and McCarthy, 1985). Moreover, numerical experiments with three-dimensional thunderstorm models have shown how inclusion of the local wind hodograph is one of the key factors in determining whether or not a severe thunderstorm becomes tornadic (Weisman and Klemp, 1984). Neither the high-resolution boundary layer winds nor the local wind hodographs are routinely available for operational use. Thus, from global-scale atmospheric phenomena down to individual cloud circulations, there is a strong need for additional wind measurements.

The observational resolution generally required to nowcast or forecast various mesoscale phenomena, as addressed in a variety of documents (e.g., Federal Coordinator for Meteorological Services and Supporting Research, 1982; The National Stormscale Operational and Research Meteorology (STORM) Program (NCAR, 1984); Shenk *et al.*, 1985; National Environmental Satellite, Data, and Information Service, 1985), is presented in Table 2. Typical phenomena associated with the items meso-α, meso-β, and meso-γ shown in the table are as follows: meso-α is the initiation of a mesoscale convective system (MCS) (NCAR, 1984), for example; meso-β is the quantitative description of the internal structure of MCS (NCAR, 1984), for example, and meso-γ is the low-level wind shear (microburst), for example.

Table 2. Required Observational Resolution

	Characteristic Resolution		
	meso-α	meso-β	meso-γ
Horizontal	100 km	10 km	0.1 km
Vertical	25 mb	10 mb	10 mb
Temporal	1 hr	10 min	1 min

The scale subdivision generally follows that suggested by Orlanski (1975) for the meso-α and meso-β phenomena. The last column in Table 2 is now generally referred to as microscale. However, the majority of requirements best fit into the global and synoptic scale and mesoscale categories. It follows from Table 2 that satellite-based remote sensing platforms would be most helpful in meeting the temporal resolution requirements at the meso-α scale.

For the meso-β and meso-γ phenomena, ground-based systems such as the Doppler radar wind profilers (Schlatter, 1985) would be more useful. However, in some situations geosynchronous cloud winds could be useful for meso-β events.

For the mesoscale, the NASA Workshop on Global Wind Measurements (1985) recommended that:

- Satellite-borne remote sensing platforms should be used to obtain 100 km (meso-α) horizontal resolution soundings of wind, temperature and moisture coincident in time and space. For temperature and moisture, satellite-based platforms should be used to obtain ~10 km resolution soundings for a variety of mesoscale events (meso-α down to meso-β).
- Accuracies should be on the order of 1 m s^{-1} for the horizontal wind components and 1 K for temperature and dew point.
- Ground-based systems should be used to fulfill high-resolution observational requirements for meso-β and meso-γ phenomena [see Table 2] for those requirements which cannot be met with space-based systems.

Most of the previous recommendations can be met by an Eos wind profiling instrument as will be discussed later. For example, with a polar orbiter, wind profiles with the required accuracy and near global coverage can be achieved. With a second polar platform and instrument, a 6-hour spatial resolution could also be achieved.

A Doppler lidar wind profiler instrument in near-equatorial orbit, such as on the manned Space Station, would result in virtually complete coverage in tropical latitudes. From both polar and near-equatorial orbits, the lidar wind instrument can also be used for mesoscale applications, though it falls short of the temporal requirements because of orbital constraints. The spatial resolution of the lidar wind instrument is determined by orbit and laser hardware considerations and also limits the mesoscale utility. However, the spatial resolution at the mesoscale can be optimized by increasing the laser pulse repetition frequency.

MORE ACCURATE DIAGNOSTICS OF LARGE-SCALE CIRCULATION AND CLIMATE DYNAMICS

Fluctuations in the climate system over one part of the globe are capable of being communicated great distances to other parts. The remarkable weather experienced in many areas of the world during the tropical Pacific El Niño event of 1982-1983 (Rasmusson, 1984) is a dramatic case in point.

The degree to which behavior in one part of the globe can be communicated elsewhere by the atmosphere appears to depend subtly on the background atmospheric state (Branstator, 1983). For instance, one such teleconnection, namely the one between the tropical Pacific and northern hemisphere extratropics, may be sensitive to the structure of the wind field in the exit region of the subtropical east Asian jet that lies between the two regions. Indications are, however, that the currently available data base is not able to depict the structure of the east Asian jet exit region sufficiently well. Thus, Rosen *et al.* (1985) found large differences between two different analyses of the zonal wind field in the area of the east Asian jet based on the data collected during FGGE, despite the apparent extensive nature of these observations. Data from a lidar atmospheric wind sounder will prove valuable if they are able to improve the quality of the wind analyses in such critical regions as the subtropical Pacific.

As might be anticipated, the quality of current operational wind analyses in the southern hemisphere is even poorer than it is in the northern hemisphere. Rosen *et al.* (1986) examined the accuracy of these analyses during 1981-1985 by comparing the differences between NMC and ECMWF time series of the atmosphere's angular momentum, which is proportional to the zonally averaged zonal wind field. When separated into latitude belts, the NMC/ECMWF differences become vanishingly small in the middle and high latitudes of the northern hemisphere, but they remain large throughout the entire southern hemisphere, reflecting the poorer distribution of wind observations in the southern hemisphere. Moreover, in the southern hemisphere high latitudes, the difference between the two analyses appears to have become larger in more recent years. Clearly, improvements in the data base are urgently required if a proper diagnosis of the global wind system is to be achieved. Referring to the previous discussion on the relative importance of mass versus wind, the results of Rosen *et al.* (1986) also provide further insight for the extratropics. Although temperatures in the southern hemisphere extratropics are provided by satellite retrievals, these do not appear to be accurate or plentiful enough to compensate for the lack of direct wind measurements.

Knowledge of the means by which the atmosphere interacts with other components of the climate system, such as the oceans or the solid Earth, is important not only to meteorologists but also to scientists in other disciplines. For example, the geodynamics community is interested in accurate, global wind measurements. Recent studies of the angular momentum balance of the Earth-atmosphere system reveal that current geodetic and atmospheric data sets are capable of detecting day-to-day changes in this balance to good precision (Morgan *et al.*, 1985). Improvements in the accuracy and coverage of the atmospheric data are desired because the geodetic measurements of changes in the solid Earth's angular momentum are expected to become significantly more accurate in the next several years.

IMPROVED UNDERSTANDING OF GLOBAL BIOGEOCHEMICAL AND HYDROLOGIC CYCLES

Life depends in sensitive ways on the weather and climate and is capable of affecting the very climate that supports it. Recognizing this, the scientific community has called for research on coupled systems, including the atmosphere, oceans, cryosphere, and biota. Two recent National Academy of Sciences reports (NAS, 1985, 1986) make a compelling case for enhanced study of the integrated Earth system, and it is not necessary to repeat their arguments here. Atmospheric dynamics plays a central role in the climate system through the horizontal and vertical transport of heat, water vapor, momentum, and trace gases.

The global wind data set obtainable from the Eos LAWS system will form a significant component of the temporally continuous global data base required for studies of coupled climate systems. This data base is needed to: (1) describe the atmospheric general circulation including the annual and interannual changes and the transports of energy, momentum, moisture, trace gases, and aerosols; (2) quantify the cycles of atmospheric variables that are key ingredients of climate change; (3) test and verify existing coupled climate models and develop new and improved ones; and (4) advance theories of climate and its variations.

Hydrologic Cycle

Water is essential to life on Earth, playing a vital role in biological processes. It is also a major factor in determining weather and climate through its effect on the radiation budget and through the energy transformations associated with its phase changes. Although the total amount of water in the oceans, atmosphere, and cryosphere is more than sufficient for human need, less than 1 percent of the total amount of water is directly and easily usable. Many regions of the world are currently experiencing severe shortfalls of water. There is evidence that, even without changes in the present climate, these shortages will spread and worsen as increasing human populations demand ever more water while at the same time altering the surface of the planet in ways that decrease the amounts and quality of usable water. For these reasons, understanding of the global and regional hydrologic cycle is assuming increasing importance. Recent National Academy of Sciences reports, such as those cited above, have identified the study of the global water cycle as one of the highest priorities among future study topics aimed at understanding global change. According to the Board on Atmospheric Sciences and Climate (NAS, 1986) Report, "The global water cycle is in many respects the most fundamental of the biogeochemical cycles."

The important components of the hydrologic cycle involve time scales ranging from hours to hundreds of years. An amount of water equal to the total global tropospheric reservoir is exchanged with the ocean and land surface every 10 days. Key components of the water cycle on this 10-day time scale include evaporation and precipitation over the land and oceans and large-scale horizontal transport of water vapor by the general circulation. Quantitative knowledge of these crucial processes over the ocean is inadequate for the comprehensive understanding of the global and regional hydrologic cycles largely because data on winds, water vapor, and precipitation are too sparse over the oceans for accurate three-dimensional analyses on daily, seasonal, and annual time scales.

A better definition of the transport of water vapor, precipitation, and evaporation over the oceans can be obtained through the use of enhanced observations of the horizontal winds and atmospheric water vapor content in improved NWP models. An important lesson from FGGE was that the combination of global observations and numerical models used together in a four-dimensional data assimilation cycle could produce greatly improved global analyses of temperature, pressure, winds, and water vapor. These analyses have been useful not only for improving operational weather forecasts, but also for many research studies. Although "ground-truth" measurements of precipitation over the ocean are necessary to verify the precipitation forecasts by these models, it is almost certain that the use of more frequent wind observations covering a greater portion of the troposphere in the four-dimensional data assimilation process will lead to significantly improved precipitation estimates over the oceans.

The global wind observations obtained from a Doppler lidar satellite system would contribute in two very important ways toward an improved understanding of global and regional hydrologic cycles. First, they would contribute directly toward a better resolution of the horizontal transport of water vapor. Second, their use in global and regional models in a data-assimilation cycle would contribute toward improved analysis and prediction of vertical motion (and vertical transport of water vapor) and precipitation. When global wind observations are used together with water vapor analyses obtained from multichannel radiometers such as those described in the Eos High-Resolution Multifrequency Microwave Radiometer (HMMR) Report (Murphy *et al.*, 1986) and other observing systems in numerical models, it will be possible to advance significantly our knowledge of the hydrologic cycle on time scales of days, seasons, and years.

Transport of Trace Gases and Aerosols

Next to water in importance to life on Earth are compounds involving carbon, nitrogen, and sulfur. There is abundant evidence that increases are occurring in the atmospheric composition of radiatively active trace gases composed of these elements, including carbon dioxide, methane, oxides of nitrogen and sulfur, as well as the chlorofluorocarbons. Many of these changes are thought to be a result of human activities superimposed on natural fluctuations, but the complex causes and relationships are not yet fully understood. Whatever the cause of these increases, the resulting changes in regional and global climates over the next 100 years could possibly exceed those ever experienced by human societies. Thus, there is an urgent need to understand the biogeochemical cycles of these elements.

Atmospheric aerosols, naturally and anthropogenically produced, are also potentially important in future climate changes. The volcanic eruptions of Agung in 1963 and El Chichon in 1982 were followed by reductions in solar radiation reaching the Earth's surface and increased longwave opacity in the stratosphere.

Two important components of biogeochemical cycles and budgets of aerosols are the horizontal and vertical transport of trace gases and aerosols, and their interactions with cloud and precipitation systems. The latter are important through their role in chemical transformations and in removal through wet scavenging. The same wind observations and models that would better define the hydrologic cycle would be useful in estimating the long-range transport of trace gases and aerosols and in establishing better estimates of precipitation systems over the oceans.

In summary, LAWS will provide improved knowledge of global wind profiles, which will have impact both in a more direct sense and in a more fundamental sense. The direct consequences will be significant improvements in numerical weather prediction. In a more fundamental sense they will provide improved understanding of atmospheric circulation and dynamics and the biogeochemical and hydrological cycles.

III. USE OF WIND DATA IN GLOBAL PREDICTION MODELS

In this chapter we discuss various atmospheric modeling activities in which wind data constitute a critical element. In particular, the impact of various components of the current observing system are discussed in the context of the present-day forecast skill. In addition, the results of observing system simulation experiments with wind profiles that might be obtained with a space-based lidar system are presented.

FORECAST IMPACT STUDIES WITH THE CURRENT OBSERVING SYSTEM

The skill of numerical forecasts has increased markedly in the past 15 years with the 500 mb height forecasts over the northern hemisphere at 5 to 6 days as accurate now as the forecasts at 2 to 3 days in the early 1970s (Bengtsson, 1986). This improvement in useful skill has been due to a number of factors such as higher resolution, an improved global observing system (mostly satellite temperatures), improved analysis techniques, and increased computer power.

The present limit of useful forecast skill is about 6.5 days in the northern hemisphere (Bengtsson, 1984) based on ECMWF statistics for the 1982/1983 winter. However, as was noted previously, this level of skill contrasts with the theoretical limit, generally accepted to be about 2 weeks. The availability of global wind profiles is a key element in allowing the current practical limit in forecast skill to be extended. Some recent data impact studies discussed below provide further insight into the importance of wind data for numerical forecasting.

Kalnay *et al.* (1985) have conducted a series of data impact experiments with the FGGE observations to investigate the relative importance of wind versus temperature data in the present observing system. In the first experiment, all of the available data were assimilated during the FGGE First Special Observing Period (SOP-1). Seven forecasts were then made every 4 days from the initial conditions provided by the assimilation. In the second experiment all temperature and moisture data were withheld. Similarly, in the third and fourth experiments all wind data and all cloud-track wind data were omitted, respectively.

The forecast results obtained by Kalnay *et al.* (1985) in the southern hemisphere indicate the importance of satellite temperature soundings because of the abundance of those data compared to the available wind data. Even with the small number of wind profiles in the southern hemisphere, the forecast skill was degraded by about 9 hours when those data were withheld. Even though they are much more plentiful, omitting single-level cloud-track winds resulted in a small degradation in forecast skill of less than 6 hours. Withholding the abundant temperature data resulted in forecasts, which were skillful beyond 3 days with the FGGE system, to lose useful skill after only 1 day.

The findings of Kalnay *et al.* (1985) were quite different in the northern hemisphere, where there is more redundancy in the data. Even though there are more temperature profiles in the northern hemisphere (satellites plus rawinsondes) than wind profiles (rawinsondes only), the results indicated clearly that the rawinsonde wind profiles are the most important component in the present observing system. Omitting the wind profiles resulted in a loss of forecast skill of about 6 hours, whereas the absence of temperatures had a smaller effect.

Observing system simulation experiments (OSSE) will now be discussed in which a more even distribution of wind and temperature profiles is envisioned in the future observing system. It has been assumed in these experiments that the additional wind profiles will be provided by a Doppler lidar wind sounder on a polar-orbiting platform.

OBSERVING SYSTEM SIMULATION EXPERIMENTS

OSSE provides a means to evaluate the potential improvement in analysis and forecast accuracy to be gained from different observing systems as well as the relative importance of different types of observations. Such studies can also assist in the design and implementation of specific observing systems.

Motivation for OSSE in the late 1960s and 1970s was provided by the initiation of GARP in 1967. One of the stated objectives of GARP was to determine acceptable compromise solutions to the data requirement problem. In order to meet this objective, the U.S. Committee for GARP proposed a national effort to study the predictive consequences of proposed observation systems, to be known as "Observing System Simulation Experiments" or OSSE. A landmark paper by Charney *et al.* (1969) ushered in the period of intense activity with OSSE. Their approach was to use a model forecast to provide a four-dimensional reference atmosphere. Starting from a perturbed initial state, a second forecast was then made with the same prediction model (the assimilation run). Simulated observations taken from the reference atmosphere were inserted into the assimilation run, and the degree to which the assimilation run approached the reference atmosphere was examined. Because the same numerical prediction model that was used to generate the reference atmosphere was also used to make the assimilation run, this type of experiment is referred to as an identical twin experiment. A number of identical twin experiments followed, for example: Halem and Jastrow (1970), Jastrow and Halem (1970), Williamson and

Kasahara (1971), Bengtsson and Gustavsson (1972), Kasahara and Williamson (1972), and Gordon *et al.* (1972).

Williamson and Kasahara (1971) were the first to question the use of identical twin experiments. They proposed, instead, an alternative, which is referred to as the fraternal twin experiment. In this approach, the numerical prediction model used for the assimilation had lower resolution and less-sophisticated physics than the model used to generate the reference atmosphere. It soon became apparent that identical twin experiments gave unrealistically optimistic results, and the fraternal twin approach gained favor. By 1974, the Joint Organizing Committee for GARP specifically ruled out the use of identical twin experiments to determine which of the possible special observing networks would be most effective during GARP.

With the advent of satellite temperature soundings, the lack of wind profiles on a global scale has been viewed as perhaps the remaining major deficiency in our observational network, as discussed in Chapter II and illustrated by the experience of operational forecasters. By the end of the 1970s, technical developments suggested that lidar methods might be able to fill this need. By 1978, the Defense Meteorological Satellite Program (DMSP) was considering such an approach, and supported a feasibility study by the National Oceanic and Atmospheric Administration's (NOAA) Wave Propagation Laboratory (WPL) (Huffaker, 1978; Huffaker *et al.*, 1980). It was concluded from the feasibility study that the idea had merit, but that it was likely to be expensive. This led to the recommendation that the benefits of such data might be thoroughly examined through OSSE.

A workshop was held at NMC in February 1983 to plan a more realistic experimental design. In order to avoid the "identical twin" problem of the earlier studies, the high-resolution (1.875° × 1.875° × 15 levels) ECMWF model was selected to produce the "nature" run and the 4° × 5° × 9 level GLA model for the data assimilation and forecasting. The nature run would provide a complete record of the "true" state of the atmosphere and would be used by NMC to fabricate the observational data as well as for verification of the forecasts.

Following the workshop, a series of simulation studies was conducted as a cooperative effort among ECMWF, NMC, and GLA to provide a quantitative assessment of the potential impact of future observing systems on large-scale NWP. Further details on the methodology and results from these experiments are described by Atlas *et al.* (1985), Dey *et al.* (1985), and Arnold *et al.* (1985). A general conclusion from the analysis/forecast experiments performed at GLA and NMC is that the use of wind profile data produces more accurate analyses and 1 to 5 day forecasts than temperature data or single-level wind data. They also showed an advance in the useful skill by as much as 24 hours in the southern hemisphere, as may be seen in Figure 2. When large analysis errors do occur on occasion in the northern hemisphere from data gaps in the conventional observing network (rawinsondes, pilot balloons, aircraft, surface, and ship reports–data used in the CONTROL Experiment in Figure 2), satellite wind profile data can be expected to reduce the error more effectively than satellite temperature soundings. Also, as in the case with the real-data impact studies, the addition of single-level winds produces less accurate forecasts than the addition of wind profiles (Atlas, 1986). The TIROS-N (Television Infrared Observation Satellite) soundings utilized in the CONTROL + TIROS-N Experiment are the simulated NOAA operational soundings. FGGE involves the cloud-track winds (CTW), TIROS-N soundings, conventional observations, and data from the other FGGE observing systems, such as drifting buoys.

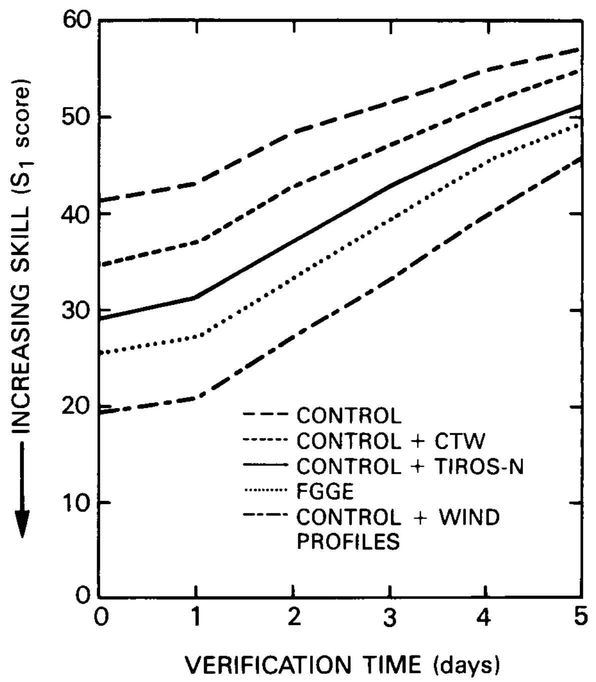


Figure 2. Impact of lidar wind profiles on simulated 500 mb forecasts in the Southern Hemisphere.

The realism of the OSSE design was also examined by comparing the forecast impact obtained with the simulated data with that found with the actual ("real") FGGE observations. The magnitude of the simulated data impact results agreed quite well with those obtained with real data in the southern hemisphere. However, the northern hemisphere forecast skill was unrealistically high for the simulated conventional data compared to the conventional real data. This was probably due, at least in part, to not imposing vertical error correlations or systematic errors on the simulated rawinsondes.

For mesoscale OSSE, the problem is even more complex and the theory is at a much earlier stage of development. The difficulties in conducting mesoscale OSSE lie mainly in the accurate simulation and verification of mesoscale circulations. Obtaining a realistic mesoscale simulation is considerably more difficult than obtaining a synoptic-scale simulation. The major reason is that a mesoscale simulation is more sensitive to physical parameterizations (such as cumulus parameterization). Another problem is that routine measurements do not allow adequate verification for mesoscale simulation.

It is also apparent that the classical skill scores (i.e., rms and S_1) used to evaluate synoptic-scale OSSE are not as suitable for mesoscale OSSE. For instance, one might get an rms error of 1 K for temperature retrievals (Kuo and Anthes, 1985) for one OSSE, which does not look significant from a synoptic point of view. However, there may be local errors as large as 5°C. This would completely change the static stability and give a different prediction for a subsequent forecast.

Further work is needed to increase the realism of simulating the future global observing system, to refine data requirements, and to evaluate the effects of more realistic wind profile observations. This includes the effect of correlated errors, coverage, resolution, and accuracy. In addition, OSSE is needed to quantitatively assess the potential usefulness of proposed observing systems for global and mesoscale NWP, local weather forecasting, and diagnostic studies of atmospheric phenomena on a variety of scales. OSSE, conducted to date, indicate a very significant potential for a space-based wind profiler system.

IV. COMPARISON OF WIND MEASUREMENT TECHNIQUES

PASSIVE VERSUS ACTIVE TECHNIQUES ASSESSMENT

Early in 1979 a Global Wind Workshop was held at the Jet Propulsion Laboratory (JPL) (Hinkley, 1979) during which the assembly of scientists discussed the application of various instruments with Earth-orbiting potential to global atmospheric wind field measurements. A general conclusion was that passive instruments had the potential for accurate horizontal wind measurements in the mesosphere and stratosphere, but not in the troposphere. Instruments such as the microwave limb sounder require a low pressure environment to reach accuracy levels of a few meters per second, which limits their application to upper stratosphere and mesosphere dynamics. Correlation spectrometers and high-resolution interferometers that sense spectral line shifts in emission spectra or scattered sunlight spectra are most sensitive in the limb-viewing mode, which restricts the practical opportunities to view the lower stratosphere along a clear line of sight. The High-Resolution Doppler Interferometer (HRDI) instrument (Hays, 1982), which is to be flown on the Upper Atmosphere Research Satellite (UARS), has a direct Earth-viewing geometry in addition to the limb-viewing geometry. At mid-tropospheric levels and lower, however, the lines used for Doppler measurement are influenced by pressure broadening, and clouds obstruct the viewing a substantial fraction of the time.

The active Doppler lidar technique was considered as the most promising for measurements at all levels throughout the troposphere. This general conclusion was upheld at the more recent NASA Symposium on Global Wind Measurements. Cloud cover remains an obstacle to wind measurement with Doppler lidar; however, the narrow transmitter footprint should aid in penetration to lower levels in areas of scattered cloud cover.

CLOUD-TRACK WINDS

Tropospheric dynamics has been inferred for over a decade using cloud-imaging data sets obtained from geostationary satellites. A discussion of the accuracy and coverage of cloud-motion-derived winds, along with their potential for future improvement, was presented at the NASA Symposium on Global Wind Measurements by Shenk (1985). The interpretation of these data is subject to controversy; several issues concerning the utility of cloud-motion-inferred winds have been discussed recently (Koch, 1985). The principal limitations of cloud motion winds determined using passive imaging sensors are: (1) winds can be measured only at the altitudes and geographical coordinates where trackable clouds exist; (2) knowledge of the cloud-top height is required; (3) high spatial and temporal resolution geosynchronous satellite systems are required; and (4) sophisticated interactive computer systems are necessary for the calculation. (Cloud-top temperatures, inferred from radiances measured by multichannel radiometers, are used to assign heights.)

Limitation (2) can be mitigated by using a stereoscopic imaging system on a satellite with the addition of a simple, scanning backscatter lidar (see the Lidar Atmospheric Sounder and Altimeter (LASA) Report) (Curran *et al.*, 1986). This combination was proposed by Lorenz and Schmidt (1979) and was recently discussed by Drescher (1986). The proposed stereo line scanner would have the following resolution: 50/100 km grid (land/sea), wind direction $\pm 5°$, wind speed ± 5 percent, ± 1 m s^{-1}, height (± 150 m). However, the cloud motions are probably more indicative of the atmospheric motions near the cloud base rather than the cloud top, which limits the height assignment accuracy even with the use of stereoscopic imaging and lidar. Further limitations associated with errors arising from non-advective cloud motions are difficult to quantify.

Limitation (4) regarding data analysis will be greatly reduced if the Monocular Electro-optical Stereo Scanner (MEOSS) is in operation (MEOSS is a DFVLR-managed (German Aerospace Research Establishment) instrument to be placed on the Indian satellite SROSS-2 (Stretched Rohini Satellite Series). The restricted spatial sampling capability will still exist. A technique such as the Doppler lidar that measures wind fields at several altitudes, with a consistent horizontal coverage, would represent a tremendous improvement.

AEROSOL PATTERN CORRELATION

Scanning lidars, which detect radiation backscattered from aerosols at visible or near infrared wavelengths, can resolve spatial variations in the backscatter cross sections, which are indicative of spatial inhomogeneities in the naturally occurring aerosols. Lidar backscatter maps, which depict the same atmospheric volume at closely spaced time intervals, often show that aerosol inhomogeneities are advected with the wind. A number of groups, including the University of Wisconsin group (Sroga *et al.*, 1980) and the Japanese NIES (National Institute for Environmental Studies) group (Sasano *et al.*, 1982), have studied the use of aerosol backscatter structure correlation techniques to determine wind speed and direction. These techniques require calculation of space-time correlation functions or Fourier transforms to best fit the data sets with a particular spatial displacement for a given time lag.

The application of this technique to global tropospheric wind measurements was discussed by Atlas and Korb (1981) and recently reviewed by Eloranta (1985). The results of ground-based measurements of atmospheric motions using this technique would appear to indicate that, within the top 20 to 30 percent of the convective boundary layer over the continents, the aerosol inhomogeneities are large enough and have a long enough coherence lifetime (minutes) to be detectable using a lidar in Earth orbit. The use of this technique to provide large-scale maps of wind fields in the upper boundary layer would require a cross scan capability and a very high laser pulse repetition frequency. The aerosol backscatter coefficients in the free troposphere are so much lower that this technique has not been demonstrated for heights above the boundary layer. It is doubtful that a lidar of reasonable size and power would be capable of observing drifting aerosol inhomogeneities consistently at altitudes throughout the troposphere up to the tropopause, even though such inhomogeneities most likely exist. In addition, propagating gravity waves or Kelvin-Helmholtz waves might provide false wind indications. Further study is required using ground-based scanning lidars.

COHERENT DOPPLER LIDARS

Range-resolved wind field measurements have been demonstrated with accuracies of approximately 1 m s^{-1} along the line of sight using ground-based and airborne coherent CO_2 lidars. Range resolutions of approximately 1 km would be typical for an Earth-orbiting system.

The coherent Doppler lidar utilizes a pulsed transmitter with a narrow spectral width approximately comparable to the Doppler shift expected from a volume of aerosol particles moving at the minimum detectable velocity. A phase-coherent photomixing receiver converts the optical or infrared frequency spectrum of the signal backscattered from the moving aerosol down to radio frequencies. At this stage radio frequency techniques can be used to amplify and filter the signal prior to the input to transient digitizers and other hardware for fast fourier transform (FFT) or multi-lag complex covariance calculations. This complex detection process is usually referred to as heterodyne detection. The transmitted pulse is short enough to provide the necessary range resolution and to avoid signal broadening due to the atmospheric-turbulence-induced coherence time.

Two coherent Doppler lidar systems, distinct from each other due to technological and operational wavelength differences, have been discussed recently as serious candidates for the global tropospheric wind measurements: (1) the coherent CO_2 lidar, operating in the 9 μm region, using a pulsed CO_2 gas discharge laser transmitter, and heterodyne detection; and (2) the coherent Neodymium-doped YAG or glass lidar, operating at 1.06 μm, using flashlamp or diode laser optical pumping of the solid-state laser medium, and heterodyne detection.

Comparisons of these and the candidate incoherent Doppler systems (discussed below) include many important tradeoffs, including efficiency, maturity of technology, reliability and lifetime, and compactness. Although many statements can be made regarding the relative capabilities and drawbacks of the technology required for each system, a comparison which is of more fundamental and time-invariant value is based on efficiency. Efficiency comparisons are made by estimating the number of transmitted photons required for a single-pulse wind velocity estimate in the middle troposphere from an altitude which is assumed to be reasonable for the Eos polar-orbiting platform.

A comparison of Doppler lidar performance requirements, which used the efficiency approach described above, was presented at the NASA Symposium on Global Wind Measurements (Menzies, 1985). This photon efficiency comparison included the above-described coherent systems and two incoherent Doppler lidar systems which would utilize tandem Fabry-Perot etalons to provide the necessary receiver spectral discrimination. The comparison was made for an assumed requirement of a 1 m s^{-1} line-of-sight velocity estimate accuracy. A more detailed analysis, extending the comparison to a range of tropospheric altitudes and a range of velocity measurement accuracies, has been recently published (Menzies, 1986). A brief account of the fundamental factors to be included in Doppler lidar efficiency follows.

Consider a pulsed lidar system which responds to aerosol backscatter signals at ranges which are large compared both with $c\tau_p$, where τ_p is the transmitter pulse duration and c is the speed of light, and also with the range gate. Let the transmitted pulse start at t = 0 and end at time t = τ_p with a temporal power profile $P_T(t)$. The received power due to the aerosol backscatter can then be expressed as

$$P_b(t) = \int_{c(t-\tau_p)/2}^{ct/2} P_T(t - 2R/c)\,\beta(R)\,(A/R^2)\eta\,O(R)\,\tau(R)dR,$$

where A is the receiver area, R is the range, η is the system optical efficiency, O(R) is the range-dependent telescope overlap function, $\beta(R)$ is the aerosol volume backscatter coefficient (m^{-1} sr^{-1}), $\tau(R)$ is the two-way transmission along the path to range R at the lidar wavelength, and where the integration over R indicates that the received power at time (t) is due to contributions from a slab of atmosphere of thickness $c\tau_p/2$ centered at $R_b = c(t/2 - \tau_p/4)$. If we assume $c\tau_p$ is small compared with the range gate, and that the dependencies of $\beta(R)$, A/R^2, O(R), and $\tau(R)$ on range over the range-gate interval can be neglected, then the received signal energy obtained by integrating $P_b(t)$ over the time interval corresponding to the range gate is proportional to the transmitted pulse energy, the aerosol β, the range-gate length, the receiver solid angle (A/R^2), the round-trip atmospheric transmission factor τ, and various system factors. (A discussion of the effects of various approximations to the previous equation on lidar backscatter measurement accuracy can be found in Kavaya and Menzies, 1985.)

The calculation of overall efficiency can proceed by considering for each system: (1) the number of photons per joule of transmitted energy per unit area of the receiver telescope (1 m^2), which are backscattered from an aerosol column as a function of altitude, the length of the column being chosen to be consistent with the desired vertical resolution; (2) the number of photons needed at the telescope primary mirror in order to measure a (single shot) Doppler shift with ± 1 m s^{-1} accuracy from the aerosol column; and (3) the electrical efficiency of each transmitter (i.e., the power draw required for the ± 1 m s^{-1} single-shot measurement accuracy of the line-of-sight component of the wind vector).

Two major coherent Doppler lidar candidates for wind profiling have been selected as "baseline." They are thought to have enough sensitivity to be capable of line-of-sight velocity estimate uncertainties in the 1 to 4 m s^{-1} range over a large percentage of the globe. The characteristics of the two baseline systems are presented in Table 3.

As stated earlier, the CO_2 Doppler lidar system has a considerable heritage, which is summarized in the following section. The neodymium Doppler lidar operating at 1.06 μm has only recently begun to be analyzed as a candidate for global wind measurements (Kane *et al.*, 1984), and simultaneous component technology developments and prototype system developments have also been started (Kane *et al.*, 1986).

Further comments regarding the efficiency calculations and expected wind measurement accuracies will follow the next subsection on incoherent Doppler lidar.

The conical scan concept is preferred for both coherent lidar systems (and the incoherent lidars as well), with a nadir angle between 45° to 55° in order to be sensitive to the horizontal wind vector and in order to achieve large spatial coverage about the orbital track. The scanning results in large Doppler shifts of backscattered signals due to the orbiting spacecraft velocity. Maximum shifts for a 55° nadir angle are given in Table 3.

Table 3. Characteristics of Baseline Coherent Doppler Lidar Systems

9 μm CO_2

Transmitter: single-frequency pulsed transversely excited atmospheric CO_2, $\lambda = 9.11$ μm, 0^{18} oxygen isotope of CO_2

Transmitter estimated electrical efficiency: 6%

Receiver: coherent detection, matched filter bandwidth in the intermediate frequency domain, local oscillator required

Turbulence effects (loss of coherence due to propagation path): no problem for 1 m diameter telescope

$\Delta\nu_1$ (1 m s^{-1} radial motion) = 200 kHz*

$\Delta\nu_{max}$ (spacecraft velocity, 55° nadir angle) = 1.1 GHz**

1 μm Nd:YAG

Transmitter: single-frequency, pulsed MOPA, diode laser pumped, $\lambda = 1.06$ μm

Transmitter estimated electrical efficiency: 5%

Receiver: coherent detection, matched filter bandwidth in radio frequency domain, tunable local oscillator required

Turbulence effects (loss of coherence due to propagation path): marginal problem for 1 m diameter telescope

$\Delta\nu_1$ (1 m s^{-1} radial motion) = 2 MHz*

$\Delta\nu_{max}$ (spacecraft velocity, 55° nadir angle) = 11 GHz**

*Frequency shift for backscatter from aerosol with 1 m s^{-1} radial velocity component.

**The frequency shift for backscatter due to the orbiting spacecraft velocity component along the line of sight for a conical scan with 55° nadir angle.

INCOHERENT DOPPLER LIDARS

Incoherent Doppler lidar measurements of winds were first carried out by Fiocco and colleagues in the early 1970s (Benedetti-Michelangeli *et al.*, 1972) using a He-Ne laser and a spherical Fabry-Perot interferometer. By measuring the Doppler shift of the laser signal backscattered from aerosols, this group (Benedetti-Michelangeli *et al.*, 1972) determined wind velocities within the boundary layer to an accuracy of a few meters per second.

Two incoherent Doppler lidars, which have applicability to global wind measurements from Earth orbit, have been discussed. The proposed systems would have a receiver consisting of a high-resolution tandem Fabry-Perot filter (along with a broader band pre-filter) and an imaging photomultiplier. This type of detection has been used in passive measurements of stratospheric and mesospheric winds from satellite (Hays *et al.*, 1981) and balloon-borne (Rees *et al.*, 1982) platforms. To utilize the technology for active measurement of tropospheric winds, lidar transmitters such as the frequency-doubled Nd:YAG (Abreu, 1979) or the Raman-shifted xenon chloride excimer (McDermid *et al.*, 1985) have been considered with the free spectral range (FSR) of the high-resolution etalon (HRE) component of the receiver being approximately 500 MHz (30 cm cavity length), rather than several GHz as was the case for the passive instruments, in order to provide a better match to the spectrally narrow backscattered laser radiation from the aerosol particles. Characteristics of these two embodiments of incoherent Doppler lidar are presented in Table 4. The detector for each system is assumed to be an image plane detector (IPD) with a 12-ring anode, optically coupled to the HRE such that an entire free spectral range would be intercepted by the twelve rings. Thus, an HRE with a finesse of 10 (corresponding to 50 MHz resolution, for example) would closely match the resolution capability of the IPD.

At the present time, neither of these two types of incoherent Doppler lidar systems has been used to measure atmospheric wind fields, although plans are underway to build and demonstrate prototype ground-based lidars using these components.

COMPARISON OF DOPPLER LIDAR TECHNIQUES

For each of the four types of Doppler lidar described in the text and in Tables 3 and 4, computations were made of the expected number of aerosol backscattered photons incident on a 1 m^2 area receiver telescope primary mirror, per joule of transmitted pulse energy, considering an aerosol column of 1 km length, located at various tropospheric altitudes as the scattering source. The results are depicted in Figure 3. In addition, similar results are shown for a

Table 4. Characteristics of Incoherent Doppler Lidar Systems

530 nm Doubled Nd:YAG

Transmitter: frequency-doubled, single frequency, pulsed Nd:YAG MOPA, diode laser pumped

Transmitter estimated electrical efficiency: 2.5%

Receiver: tandem Fabry-Perot etalon, HRE gap = 30 cm (FSR = 500 MHz), IPD with 12-ring anode

Turbulence effects: no problem for 1 m telescope

$\Delta\nu_l$ (1 m s^{-1} radial motion) = 4 MHz*

$\Delta\nu_{max}$ (spacecraft velocity, 55° nadir angle) = 22 GHz**

350 nm Raman-shifted XeCl

Transmitter: Raman-shifted, single-frequency XeCl excimer, injection-controlled

Transmitter estimated efficiency: 4%

Receiver: tandem Fabry-Perot etalon with HRE gap = 30 cm (FSR = 500 MHz), IPD with 12-ring anode

Turbulence effects: no problem for 1 m telescope

$\Delta\nu_l$ (1 m s^{-1} radial motion) = 6 MHz*

$\Delta\nu_{max}$ (spacecraft velocity, 55° nadir angle) = 32 GHz**

*Frequency shift for backscatter from aerosol with 1 m s^{-1} radial velocity component.

**The frequency shift for backscatter due to the orbiting spacecraft velocity component along the line of sight for a conical scan with 55° nadir angle.

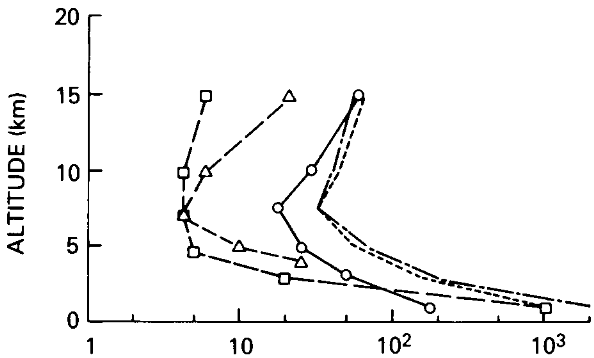


Figure 3. Number of photons per joule of transmitted energy received per unit area of receiver telescope (1 m²) as backscattered from a 1 km aerosol layer as a function of layer altitude and measured or calculated wavelength: measured λ = 10.6 μm Δ— —Δ, λ = 9.2 μm □— —□; calculated λ = 350 nm o——o, λ = 530 nm - - - -, λ = 1.06 μm — - —. The Earth-orbiting-platform height is 800 km.

10.6 μm Doppler lidar. The assumed aerosol backscatter profiles are, in the case of the 350 nm, 530 nm, and 1.06 μm wavelengths, based on unpublished Air Force Geophysics Laboratory (AFGL) models which are, in turn, based on extensive visibility and aerosol sampling data sets. The wavelength dependence of the aerosol backscatter in the free troposphere is assumed to be $\lambda^{-1.2}$ in this spectral region. The aerosol backscatter profile for the 9 μm wavelength is based on a number of actual backscatter profiles taken from a ground-based lidar at JPL in Pasadena, California. (See Menzies, 1986 for more detailed comments.) The 10.6 μm backscatter profile was measured by a ground-based lidar at NOAA-WPL in Boulder, Colorado (Post, 1985).

Referring to Figure 3, the large difference in aerosol backscatter coefficients between the near-ultraviolet/mid-visible wavelengths and the 9 to 10 μm wavelengths (e.g., 6×10^{-8} m^{-1} sr^{-1} at λ = 500 nm versus 2×10^{-10} m^{-1} sr^{-1} at λ = 9.25 μm at 5 km altitude) is largely compensated, of course, by the fact that a 1 J pulse contains 20 times as many photons at 10 μm wavelength as does a 1 J pulse at 500 nm wavelength. The Rayleigh scattering loss also accounts for a large factor in the near-ultraviolet.

As stated earlier, the next step in the overall efficiency comparison is the estimation of the number of photons needed at the receiver telescope mirror in order to measure a (single shot) Doppler shift corresponding to a pre-selected accuracy of the line-of-sight components of the (horizontal) wind vector.

Required transmitter pulse energies are indicated in Figure 4 for a range of line-of-sight velocity estimate uncertainties when probing a column of aerosols centered at 5 km altitude, assuming a range-gate consistent with 1 km vertical resolution. *Using the best available data and assumptions for optical losses and quantum efficiencies, one concludes that the coherent lidar receivers are an order of magnitude more efficient than the incoherent receivers when the goal is a ±1 m s⁻¹ estimate uncertainty. (The gap narrows as the uncertainty of the estimate is allowed to increase to ±4 m s⁻¹) (Menzies, 1986).*

Eye safety is a major problem with the coherent 1.06 μm lidar. The diffraction-limited transmitter beam divergence is so small that calculations using the American National Standards Institute (ANSI) recommendations (Sliney and Wolbarsht, 1982) indicate that the maximum permissible exposure level for an unaided night-adapted eye would limit the transmitted pulse energy to no more than 40 mJ. (This result is based on the "safety" factors of 3X for variations in intensity across the beam footprint and 10X for atmospheric-turbulence-induced scintillation.) Thus the coherent 1.06 μm lidar is hampered by eye safety considerations to the extent that the possibility for Earth-orbiting coherent Doppler lidar using solid-state laser technology rests on the hope that technology advances may result in development of a similar system at a slightly longer wavelength (λ ≥ 1.5 μm) with no loss of overall efficiency when compared with the 1.06 μm Neodymium lidar system.

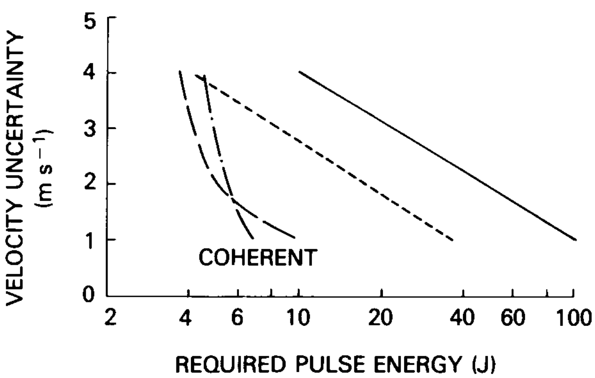


Figure 4. Dependence of required transmitter pulse energy on radial velocity estimate uncertainty and wavelength: λ = 350 nm ——, λ = 530 nm - - - -, λ = 1.06 μm — · —, λ = 9.11 μm — —. A 1.75 km slant range resolution corresponding to a 1 km vertical resolution is assumed. The Earth-orbiting-platform height is 800 km.

SUMMARY OF COMPARISONS

An ideal wind profiling system should provide global measurements of wind speed and direction at several heights over a grid comparable in size to that of the current radiosonde network. In principle, several techniques have the capability to at least partially meet this need under certain conditions. These techniques are in various stages of development. *Clearly, however, at this time the leading candidate* *for a spaceborne wind sensing system is CO_2 Doppler lidar.*

Since Doppler lidar systems employing CO_2 transmitters have been used for approximately 2 decades, a broad base of experience exists covering all aspects of the wind sensing problem, including transmitter and receiver configurations, atmospheric propagation, aerosol backscatter characteristics, and signal processing. During the past 5 years, a pulsed Doppler lidar conceptually similar to a potential spaceborne instrument has been used in several atmospheric science experiments investigating wind field structure; the characteristics of such measurements are well documented and understood. *This broad heritage of CO_2 lidar wind measurements demonstrates that these instruments can perform the task of measuring global winds.* (The heritage is discussed in more detail in Chapter V.)

Other potential techniques are in much earlier stages of development or require more measurements to resolve certain questions. A coherent Nd:YAG lidar operating at 1.06 μm should have the capability to perform approximately as well as a comparable CO_2 system, based on the analysis in the previous section. Additionally, Nd:YAG lasers pumped by laser diode arrays offer reliability advantages associated with solid-state lasers. The capability of producing frequency-stable pulses from a Nd:YAG transmitter has only recently been demonstrated (Kane *et al.*, 1986), but to date, no actual Doppler measurements have been documented. Thus, no experience base comparable to that associated with CO_2 technology exists from which to begin evaluating the technique for space-based measurements. The lack of maturity in coherent Nd:YAG lidar technology is compounded by the problem of eye safety associated with operation at the 1.06 μm wavelength. Ultimately, it is expected that a new source, such as erbium:YAG that operates at a slightly longer wavelength but possesses the other properties of Nd:YAG, will have to be developed. Thus, in essence, near-infrared solid-state technology will have to advance and be evaluated through two development cycles.

Incoherent Doppler lidar and aerosol pattern correlation techniques appear to be less viable candidates for a spaceborne wind measuring system. No measurements of free atmospheric winds have been demonstrated using the incoherent Doppler lidar techniques, although similar methods have been employed for passive wind measurements in the stratosphere and mesosphere. Additionally, the analysis in the previous section indicates that the efficiency of such systems is lower than that of coherent Doppler systems, especially if accuracies on the order of 1 m s^{-1} are desired. Aerosol correlation techniques, while applicable in the boundary layer, appear to have serious deficiencies due to a lack of aerosol and presence of waves when applied to the free troposphere. No free tropospheric wind measurements using the aerosol correlation technique have been demonstrated.

In summary, at the present time, the CO_2 Doppler lidar technique is the technique of choice to pursue for global wind measurements. Several factors support this conclusion: (1) the instrument heritage is broad; (2) the technique has been well-demonstrated; (3) the laser operates in an eye safe region; and (4) the efficiency is expected to be comparable to or better than efficiencies that can be obtained using alternative techniques. Because of this clear advantage, the remainder of this document will focus on CO_2 lidar as the leading technique for incorporation into LAWS. Chapter V describes the heritage of CO_2 Doppler lidar; Chapter VI describes pulsed Doppler lidar transmitter technology; while Chapter VII summarizes past studies relating specifically to wind measurement from space platforms. Chapter VII also describes the status of current knowledge on the global backscatter coefficient distribution as it relates specifically to CO_2 spaceborne lidar. Chapter VIII outlines data handling considerations for LAWS. Chapter IX outlines a strategy for development of a global wind sensing capability and describes the final development steps necessary to extend current CO_2 lidar technology so it can be applied for spaceborne wind measurements from orbiting platforms.

V. COHERENT DOPPLER LIDAR INSTRUMENT HERITAGE

CONTINUOUS WAVE COHERENT CO_2 DOPPLER SYSTEMS

Wind Measurements

The earliest Doppler lidar wind measurements (Huffaker *et al.*, 1970) were continuous wave (cw) measurements of clear air returns. These cw Doppler systems were the precursor of the pulsed Doppler lidar systems which are the primary focus of this report.

Lawrence *et al.* (1972a) and later Post *et al.* (1978) showed good agreement between the cw Doppler lidar wind measurements and conventional wind measurements. Several techniques evolved in the 1970s for measuring three-dimensional wind velocities with cw Doppler lidar systems. Lawrence *et al.* (1972b) proposed a technique which employed three separate systems focussed at a common region of space to obtain the vector air motion. Cliff and Huffaker (1974) described a technique which utilized a conical scanning approach known as velocity azimuth display (VAD) originally employed with radar systems (Lhermitte and Atlas, 1961). Bilbro and Jeffreys (1975) described another technique using two cw systems scanning in a common plane.

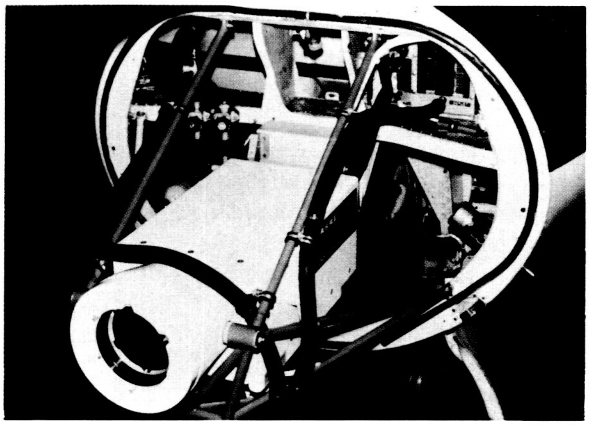
A wide-ranging program of measurements with cw systems has been under way at DFVLR for some years (Koepp *et al.*, 1984; Werner *et al.*, 1984). The system incorporates a 4 W cavity laser, 30 cm Cassegrain transmitter, and surface acoustic wave (SAW) signal processing built by GEC (General Electric Corporation) Avionics. Several technical innovations have been investigated including the use of an optical amplifier and homodyne to heterodyne conversion by use of a transverse mode spacing. The system is mounted in a mobile van. Wind profiles in the planetary boundary layer and over the sea surface have been obtained using the DFVLR system.

Several authors have reported field measurements using cw Doppler lidars to observe the velocity structures of dust devils (Schweissow and Cupp, 1976; Jeffreys *et al.*, 1976; Bilbro *et al.*, 1977) and water spouts (Schweissow *et al.*, 1977).

Aeronautical Measurements

Munoz *et al.* (1974) described a cw system which was used to perform true airspeed measurements aboard the NASA/Ames CV-990. These measurements were performed in 1972 with a 50 W CO_2 system. Measurements were made under clear weather conditions up to altitudes of 3 km.

After several years work with large laboratory type systems a compact remotely operable airborne system was built at the Royal Signals and Radar Establishment (RSRE) for installation in the HS125 aircraft at Royal Aircraft Establishment (RAE) Bedford, United Kingdom. This system, which has been described in several articles, e.g., Vaughan and Woodfield (1983, 1984), incorporates a 4 W cw CO_2 waveguide laser locked to the P20 transition at 10.6 μm, a 15 cm germanium lens telescope, and a Joule-Thomson-cooled wide band detector. SAW signal processing is employed over a bandwidth of 0 to 62.5 MHz with digital integration of weak signals. The all-up weight of the optics head (Figure 5) is less than 60 lbs. An outstanding feature has been the long-term reliability. Several hundred flights have now been made in varying conditions including the Joint Airport Weather Studies (JAWS) exercise in Colorado in 1982. Shown in Figure 6 are data from the JAWS experiment taken in a turbulent microburst. In 5 years of operation there have only been four stand-down periods of which two have been associated with the optics and laser. During one period of over 2 years the equipment operated at full sensitivity without any adjustment whatsoever.



(a)

(b)

Figure 5. (a) The optics head of the RSRE/RAE laser true airspeed system mounted in the unpressurized nose of the HS125 aircraft. (b) Nose cone in place with the 8 in. germanium transmitting window at the front.

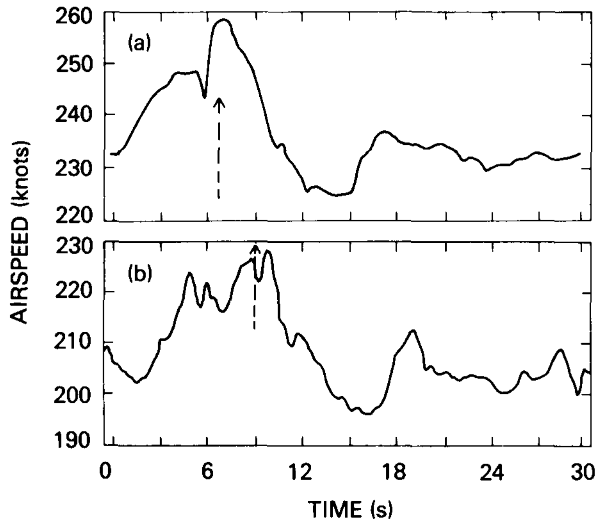


Figure 6. Record of a thunderstorm microburst recorded by the RSRE/RAE laser true airspeed system during the Joint Airport Weather Studies project in Colorado. The laser true airspeed in (a) shows a 40 knot wind shear up to 2.5 s ahead of the on-board-pitot-static-computed airspeed of (b) (JAWS Project, Flight 792, 14 July 1982).

Huffaker *et al.* (1975) reported on a scanning system designed specifically for vortex tracking and presented preliminary results from a test undertaken at the John F. Kennedy (JFK) International Airport. Bilbro *et al.* (1976) provided detailed results of the JFK tests, which included the time histories of some 1,600 vortex tracks. Vortex locations were obtained to an accuracy of 3 m and were tracked for durations in excess of 80 s and to ranges of 1,500 m. Vertical and horizontal transport information was recorded and circulation strength measured.

Vortex measurements were also performed at RAE Bedford and Heathrow Airport in the United Kingdom in 1974. Alexander *et al.* (1977) described a scanning system which was developed for more extensive vortex measurements by this system.

Hallock *et al.* (1977) reported on the measurement of wake vortex characteristics of a B-747 aircraft in various configurations. These measurements were performed in support of a vortex alleviation program. Detailed velocity profiles obtained during this test were provided by Burnham *et al.* (1978). In this report the profiles showed vortex decay from the edge toward the center. The tests also appeared to indicate that vortex descent in a stratified atmosphere accelerated vortex decay.

In 1977 the Transportation Systems Center (TSC) acquired its own system (Brashears *et al.*, 1977). Since that time TSC has performed or sponsored measurements at a number of airports throughout the country, and participated in tests in Canada. These tests have dealt with, and are continuing to deal with, vortex tracking under a variety of conditions of takeoff and landing as well as special configurations.

Backscatter Measurements

A cw lidar for backscatter measurements was developed by the Marshall Space Flight Center (MSFC) and flown in 1981, 1982, 1984 and 1986 (Jones *et al.*, 1981, 1984; Bilbro *et al.*, 1986). This system was designed to measure the backscatter in two different modes: the volume mode and the single particle mode at the 10.6 μm wavelength. A similar system operating at the isotopic wavelength of 9.11 μm is under construction.

The RSRE airborne system has also been used to perform backscatter measurements. For this role, a careful systems calibration has been conducted and shows that for 10^4 integrations over a 0.6 s period a minimum backscatter sensitivy of $\sim 3 \times 10^{-11}$ m^{-1} sr^{-1} is achieved. Agreement of theoretical and calculated signal-to-noise ratios is found to be within ~2 dB. With an operational ceiling of 43,000 ft. (~13 km), measurements of backscatter have on occasion been extended into the lower stratosphere. A wide range of backscatter data has now been accumulated in northern Europe, Colorado, off Gibraltar, and the Arctic, and is summarized in Table 5.

Table 5. Summary of Backscatter Measurements [$\beta(\pi)$ in m^{-1} sr^{-1}]

United Kingdom	Summer: usually $> 10^{-10}$ m^{-1} sr^{-1} to 10 km
	Winter: often remarkably clear above inversions but usually $> 10^{-10}$ to 6 km and $\sim 10^{-10}$ above
Colorado	JAWS Summer 1982: usually $> 10^{-10}$ to 13 km
Arctic	Summer 1982, 4 flights: very variable with haze layers at ~8 km
Gibraltar	Summer, 2 flights: 5×10^{-10} to 12 km including haze layers, $> 10^{-8}$ at 11 km, and a few thin layers $\sim 10^{-10}$ at 5 km
	Winter, 2 flights: $> 10^{-10}$ to 5 km, $> 4 \times 10^{-11}$ at 5 to 10 km

During the winter and spring of 1985-1986, further measurements have been made over the United Kingdom, and over northern Norway and into the Arctic circle. During April, three flights coincident with passage of the Stratospheric Aerosol and Gas Experiment (SAGE) II Limb-Sounding Satellite were made. Extensive measurements over path lengths >100 km at 13 km altitude were made, which should provide valuable data for cross reference of the 10 μm backscatter with the extinction data of the satellite at different wavebands. A photograph taken during this trial is shown in Figure 7. The backscatter data are presently being evaluated.

Recently a compact CO_2 lidar built by Crouzet (see Figure 8) was flown over France on a Caravelle research aircraft to take backscatter measurements (Morbieu and Mandle, 1986). More than 20 flights, up to an altitude of 10 km, were conducted during a 4-month period between January and May 1986. More flights will be operated in the near future in coordination with the Global Backscatter Experiment (GLOBE) to be discussed later. The scientific results will be included in the GLOBE data base.

PULSED DOPPLER SYSTEMS

Airborne Measurements

The desire to detect clear air turbulence (CAT) provided much of the early impetus in the development of pulsed CO_2 lidars. Gibson (1966) proposed a system which was to detect the Doppler frequency shift as an indicator of CAT. Weaver (1971) described a pulsed lidar system which was being developed to detect CAT. This system (Jelalian *et al.*, 1970) was flown on a shakedown flight in 1971 and was flight tested in 1972. Preliminary results of these tests were described by Huffaker (1974). He reported true airspeed measurements as an outcome of the 1972 CAT flight tests with a pulsed system. Measurements in these tests were reported to altitudes of 6 km. These results indicated that clear air velocity measurements at ranges of 4 to 6 km and altitudes up to 6 km could be consistently obtained. Mountain-wave CAT was detected and verified by aircraft penetration, and a wind shear in a dust storm was detected. Following the tests, the pulsed system was reworked and taken through a series of ground tests. The system was flown again in the winter of 1979.

In 1978, modifications were begun to the pulsed lidar to provide two-dimensional mapping of the wind field in a horizontal plane at the altitude of the aircraft. The system was flown in 1981 and successfully demonstrated the ability to map the wind fields in and around thunderstorms (Emmitt, 1985a) and orographic features (Bilbro *et al.*, 1984). The scan pattern is depicted in Figure 9. Figure 10 shows the wind-field map generated near a thunderstorm. This figure demonstrates the result of strong outflow mixing with the ambient wind field. A color display of the velocity distribution on a scan-by-scan basis is shown in Figure 11. In this figure, gravity waves can be seen appearing in both the forward and aft scan displays.

After the 1981 flight tests, the system was modified to incorporate an inertial platform and flown

Figure 7. Photograph of the setting sun taken from the HS125 aircraft in April 1986. This flight over the United Kingdom was timed to coincide with passage overhead of the SAGE II Limb-Sounding Satellite. Aerosol backscatter data at 10.6 μm from the RSRE/RAE laser true airspeed system on the aircraft provide a comparison with the satellite extinction measurements.

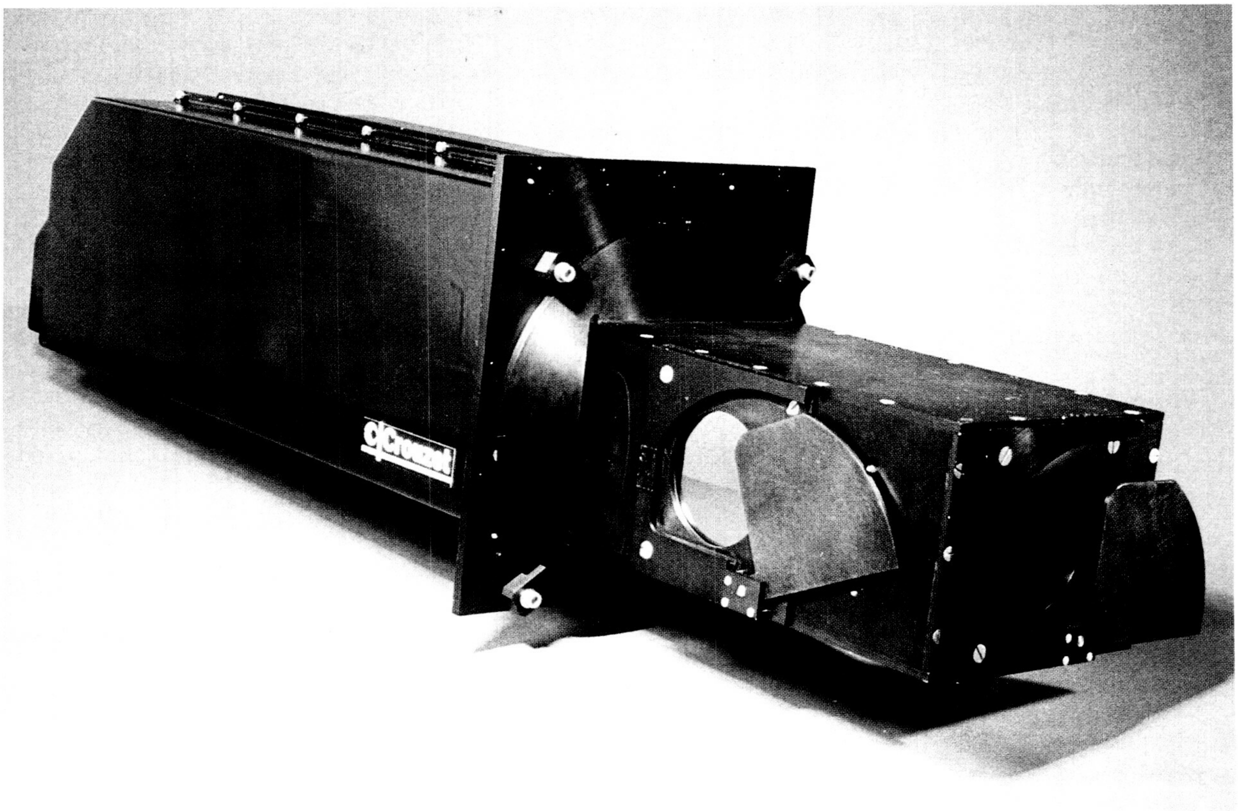


Figure 8. The cw CO_2 coherent Doppler lidar developed by Crouzet (France) for true airspeed measurements on board a helicopter or an airplane. This breadboard instrument is also used to make *in situ* measurements of the atmospheric backscatter coefficient at 10 μm.

again in 1984. The results of this flight test are reported by Bilbro *et al.*, (1986). The system utilizes a 10 mJ master oscillator power amplifier (MOPA). Color displays obtained from the 1984 flight tests near the Carquenez strait in northern California are shown in Figures 12 and 13. These figures represent slices through the atmosphere at different levels and show the vertical propagation of cellular velocity structure.

In 1985, JPL began the construction of an airborne pulsed lidar to measure backscatter as part of GLOBE. The system employs a 0.5 J CO_2 transversely excited atmospheric (TEA) laser operating at a pulse repetition frequency of 5 Hz. The system is planned for completion in 1987 and will be flown on the NASA Ames DC-8 in 1988 as part of the GLOBE program.

Ground-Based Measurements

The first ground-based measurements with a mobile pulsed Doppler lidar were reported by DiMarzio *et al.* (1979). These measurements were of a thunderstorm gust front and associated wind shear. A time history of the gust-front passage is shown in Figure 14. This figure presents successive plan-view velocity maps created by scanning the system in azimuth and range. A wind shear in excess of 40 m s^{-1} was detected at one point during the passage of the gust front.

Although the first ground-based measurements were made using a MOPA-type system, a key element in the evolution of Doppler lidar has been the development of frequency-stable, pulsed CO_2 TEA lasers for use in ground-based systems. Because transmitters using TEA lasers typically operate at higher efficiencies than MOPA transmitters, they are more applicable for space-based systems. Development of the first TEA laser system for Doppler wind measurements began in 1978.

Following a successful demonstration of the laser's capabilities, the essential system hardware was purchased by NOAA and incorporated into a trailer-mounted transportable system. First measurements from the NOAA pulsed lidar were obtained in 1981. Over the subsequent 4 years, the system demonstrated that a coherent lidar incorporating a TEA laser could be moved to different locations and operated successfully on a routine basis. The transmitter operated without significant problems until it was replaced in late 1985 with a higher energy, second-generation transceiver. *At the time of its retirement, the original lidar had produced well over 10 million shots and was operating perfectly.*

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COLOR PHOTOGRAPH

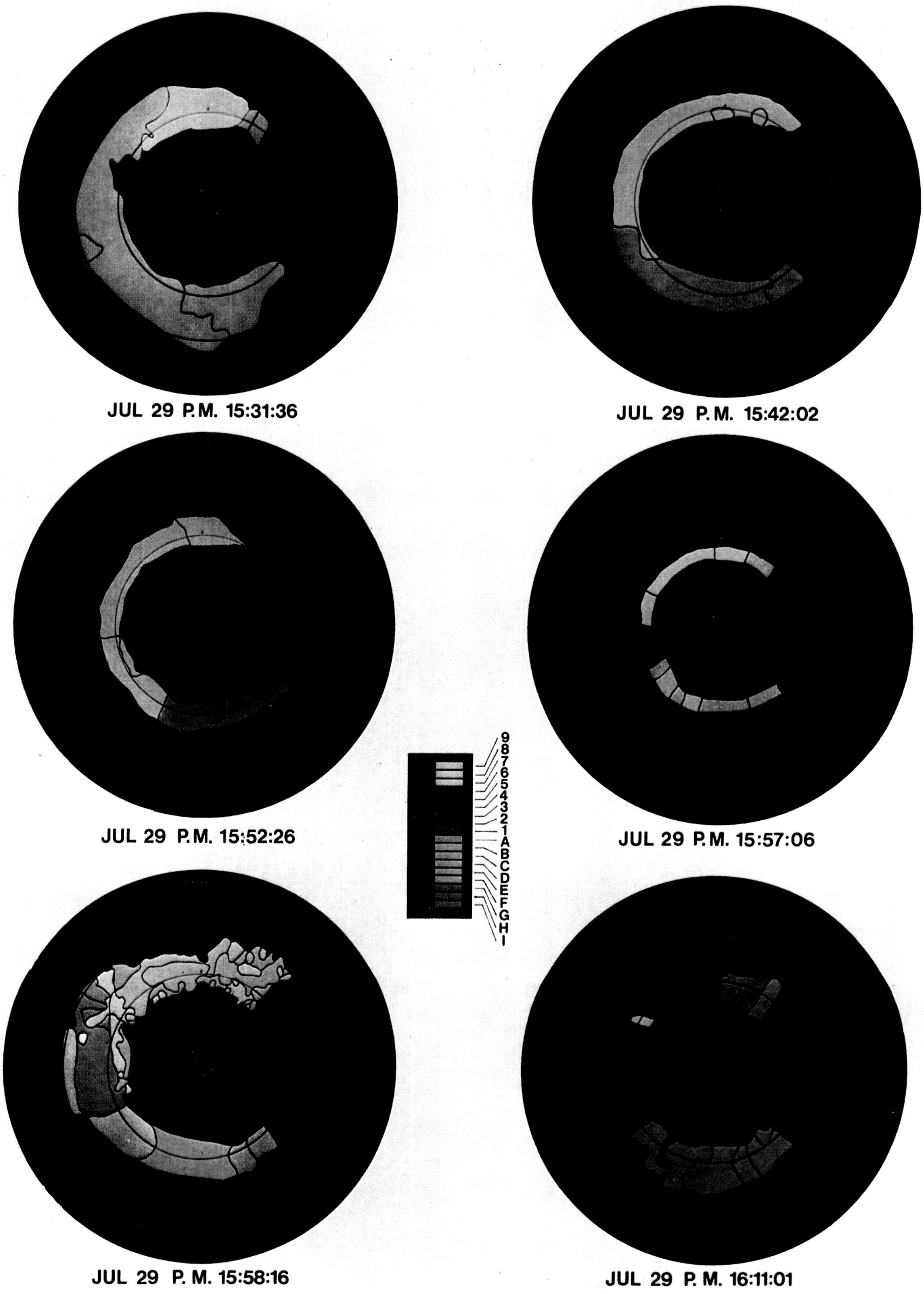

Figure 14. Ground-based pulsed Doppler lidar gust-front measurement.

The original NOAA transceiver used a hybrid-TEA configuration to obtain the required frequency stability (Post *et al.*, 1981). An intracavity, low-pressure, cw CO_2 laser, frequency-locked to line center by means of an active servo loop, seeded the TEA laser at a single frequency to produce approximately 100 mJ of single-longitudinal-mode energy per pulse at a 10 Hz pulse repetition rate. Length of the transmit pulse was on the order of 3 μs using a 7:1:1 laser gas mixture of He, N_2, and CO_2, although approximately 15 percent of the total energy was contained in the pulse tail stretching out to 7 to 8 μs. When the nitrogen was removed from the mix, the laser produced a 1 s duration pulse with a nearly perfect Gaussian shape (no tail), but containing only 10 mJ of energy.

Performance tests using calibrated targets showed that the sensitivity of the NOAA lidar was within a few decibels of the theoretical value. Calculations included system effects such as heterodyne efficiency, transmission losses, focussing, and atmospheric absorption. Frequency stability was also very good: pulse-to-pulse variability was less than the equivalent of a few tenths of a meter per second. Such performance combined with a real-time processing and display capability has enabled the NOAA lidar to be used as a data source in a wide variety of atmospheric science experiments. For example, by periodic conical scanning, the lidar can examine the temporal variability in the local wind profile. Figure 15 illustrates a PPI scan taken at an elevation angle of 20°, showing a wind field containing a pronounced low-level jet. Figure 16 shows a wind profile during a similar low-level jet event computed by the VAD technique (Browning and Wexler, 1968). Such profiles have been measured as often as 6 times per hour over several hours, illustrating evolution of the wind profile during transient events such as the passage of upper-level fronts.

In addition to its profiling capability, the NOAA lidar has been valuable for studying transient, local-scale phenomena such as passage of frontal boundaries or evolution of terrain-induced drainage flows. During the JAWS program in 1981, the NOAA lidar operated in conjunction with the Marshall MOPA system to measure two-dimensional wind fields over an area greater than 50 km^2 (Emmitt, 1984; Rothermel *et al.*, 1985).

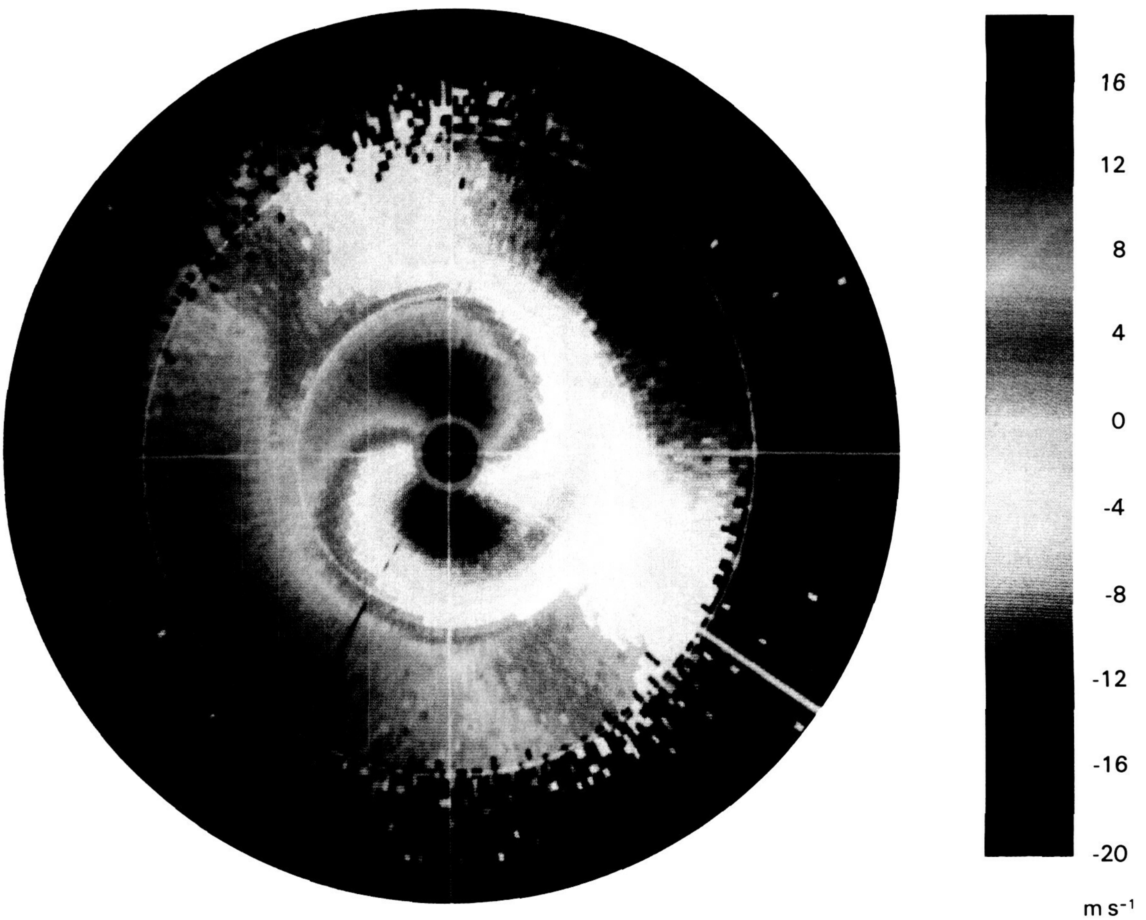

Figure 15. Plan-position-indicator display of radial winds for azimuthal scan taken at a 20° elevation angle near Midland, Texas. The pinwheel-like structure in the wind field is indicative of the shear associated with the low-level jet.

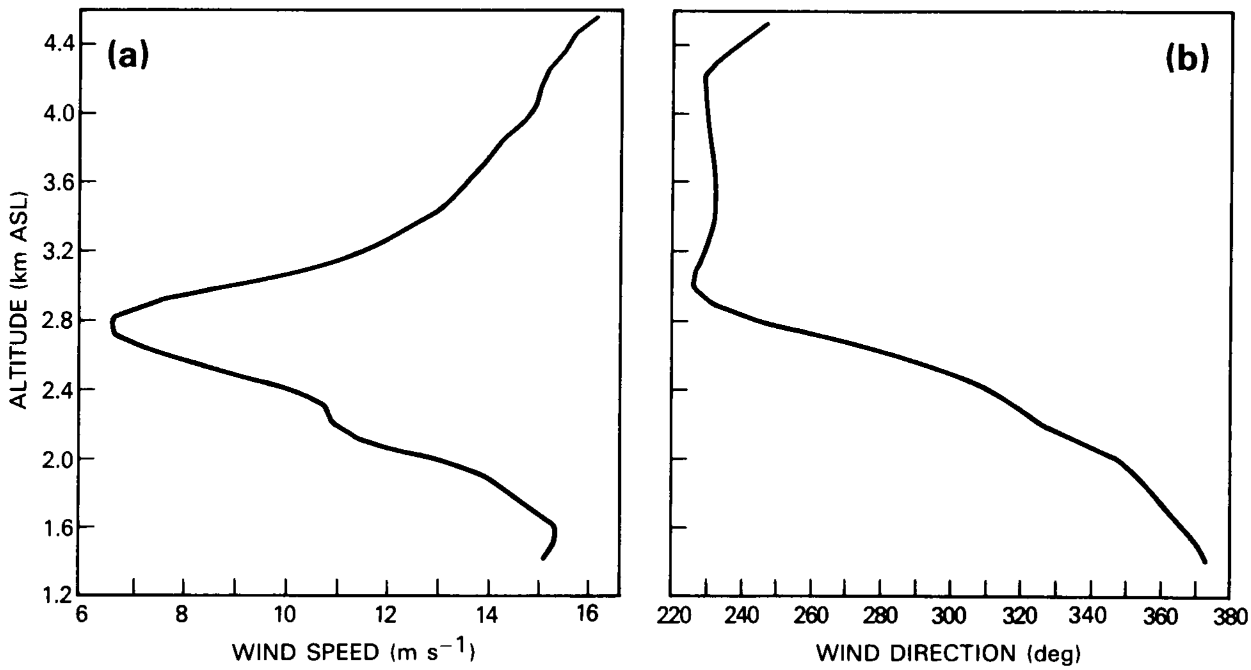

Figure 16. Wind direction (a) and speed (b) profiles computed from the plan-position indicator measurements shown in Figure 15. Profiles are obtained by fitting a sinusoid to the plot of radial wind speed versus azimuth at each range.

VI. PULSED DOPPLER LIDAR TRANSMITTER TECHNOLOGY

REQUIREMENTS AND CANDIDATE TECHNIQUES

A spaceborne coherent CO_2 Doppler lidar requires a transmitter with a highly stable emission frequency (0.2 to 0.4 MHz) over a several microsecond duration, with a high output energy at a pulse repetition rate of about 10 Hz. A high energy conversion efficiency is also required to limit the primary electrical power to a reasonable level. Since the desired operating wavelength is 9.1 μm, a grating or alternative dispersive element is required to select the proper laser line.

A high energy per pulse requires high gas pressure (0.5 to 1.0 atm.) and a large active volume. In addition to a high energy output, a low-divergence (diffraction-limited) beam emission associated with high-transverse-mode discrimination is also needed. These two requirements can be met by using an unstable resonator configuration (Siegman, 1974).

A high operating pressure and a long-cavity resonator result in a natural multimode emission from a CO_2 TEA laser. Several longitudinal cavity resonances fit within the CO_2 linewidth. Since heterodyne detection requires a single-longitudinal-mode (SLM) transmitter, various methods have been proposed to achieve single-mode selection: (1) increasing the laser intracavity spectral density at one frequency (one longitudinal mode) near threshold by injection of external power from a master oscillator (Lachambre *et al.*, 1976; Megie and Menzies, 1979); (2) increasing the intracavity intensity and the molecular gain by using a hybrid configuration (Gondhalekar *et al.*, 1975; Pace and Cruickshank, 1980) where a low-pressure cw CO_2 section is operated either above or below threshold with the cw section and the main TEA section placed in the same resonator; and (3) increasing the cavity losses at undesirable mode frequencies by inserting one of several selective elements, such as Fabry-Perot etalons, into the resonator for SLM selection. This technique is limited to applications requiring low pulse energies due to optical damage sensitivity of the etalons. The use of Gaussian mirrors in a resonator (McCarthy and Lavigne, 1985) could be a valuable improvement to the unstable resonator for high-order, transverse-mode discrimination. Although promising, it remains to be demonstrated for high-pulse-energy applications.

Recently, a new method based on phase conjugation has been proposed. It is an elegant technique for obtaining single-mode pulses with high frequency stability. This phase conjugation technique with CO_2 lasers (Ouhayoun, 1985), although promising, remains to be demonstrated for high-pulse-energy applications. In addition to single-mode selection, line-by-line tunability can be obtained by using a diffraction grating.

A possible alternative to the injection-controlled and hybrid configurations is the amplification of a slice of several microseconds from a master oscillator in a high-power multipass amplifier. A careful design of the amplifier is required to avoid amplified spontaneous emission (Figueira and Novak, 1980).

A MOPA lidar system has been tested on the ground (Teoste and Capes, 1978) and in an aircraft (Bilbro *et al.*, 1984) using cw master oscillators with the required frequency stability. However, the overall efficiency of a MOPA system when using a cw master oscillator is low, which is a severe drawback for a spaceborne lidar system. An alternative master oscillator would be a small-scale TEA CO_2 laser, operating at sub-atmospheric pressure in order to generate pulses of several microseconds duration. It would be designed for high frequency stability.

For injection at a cavity mode resonance very near the CO_2 line center, the external intensity required for SLM selection during the gain switched spike (GSS) is very low (about 10 μw cm^{-2}). The mode selection region around a cavity resonance can be a large fraction of FSR (Flamant *et al.*, 1983). It varies in a logarithmic manner as a function of the injected intensity. However, more injected power is needed to maintain SLM emission over a several microsecond pulse duration. Using a waveguide laser, injection locking is not restricted to line center (Megie and Menzies, 1979). The injection-locking technique leads to a reduction of the amplitude of the GSS and to a temporal advance in the onset of the pulse. At very high injected power density levels the output pulse energy can be nearly equally distributed over the entire pulse duration, which is preferable for wind measurement. With the injection-locking technique, a pulsed injection oscillator works as well as a cw laser (Meyer, 1976; Menzies *et al.*, 1984a), but it requires a good synchronization of both lasers.

The laser dynamics in a hybrid configuration when the cw section is operated above threshold is quite similar to the dynamics in the injection-controlled configuration, because in both cases there exists at the time lasing threshold is reached a substantial intracavity intensity at the selected mode frequency. In a hybrid configuration, however, the pulsed laser emission is restricted to the low-pressure Doppler linewidth. There is no tunability, which could be a limitation when considering the chirp effect associated with a pressure shift of the CO_2 line center (i.e., the line center frequency for the low-pressure intracavity gain cell is displaced from the line center frequency for the atmospheric pressure TEA discharge section).

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COLOR PHOTOGRAPH

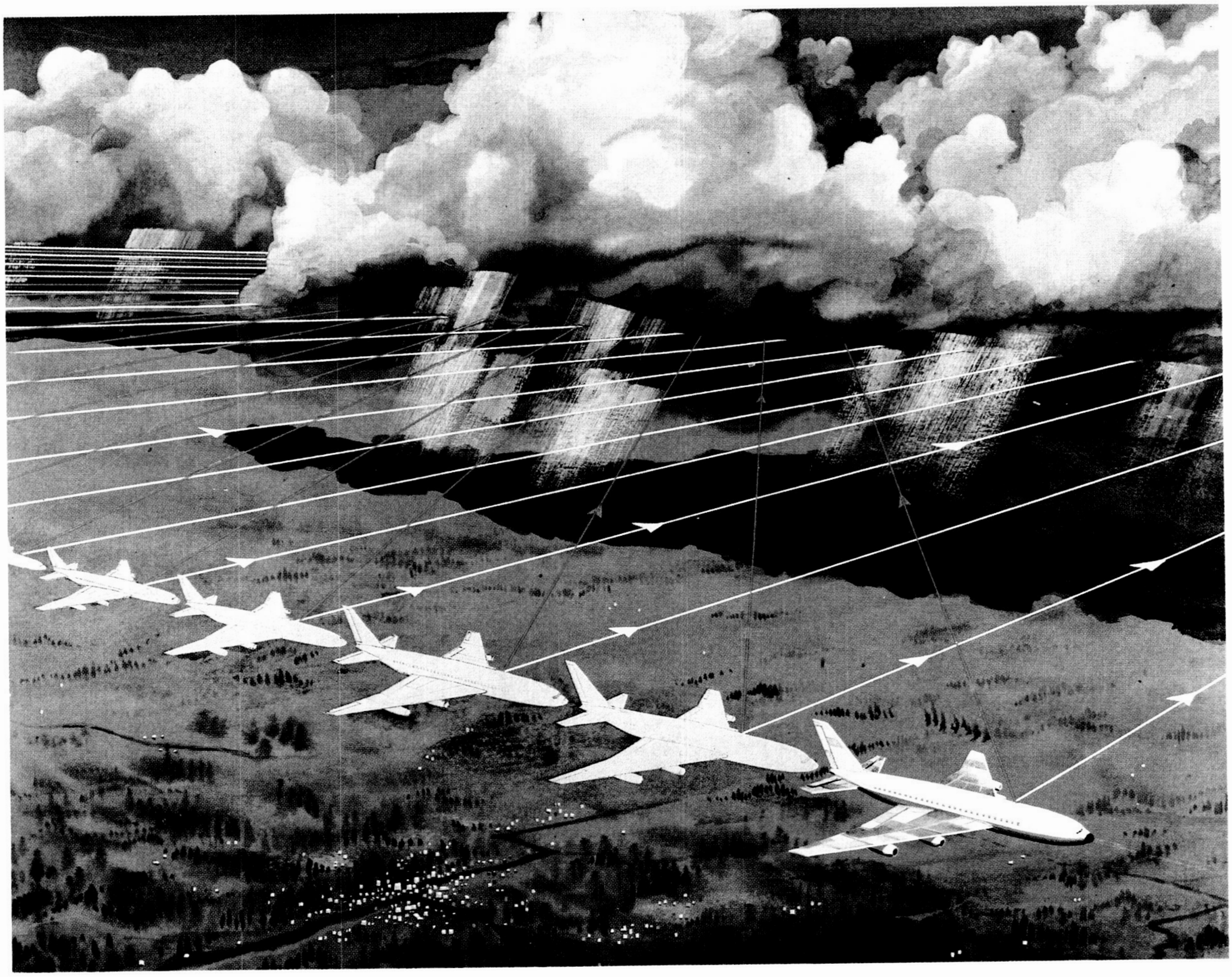

Figure 9. Severe storm wind measurement scan pattern.

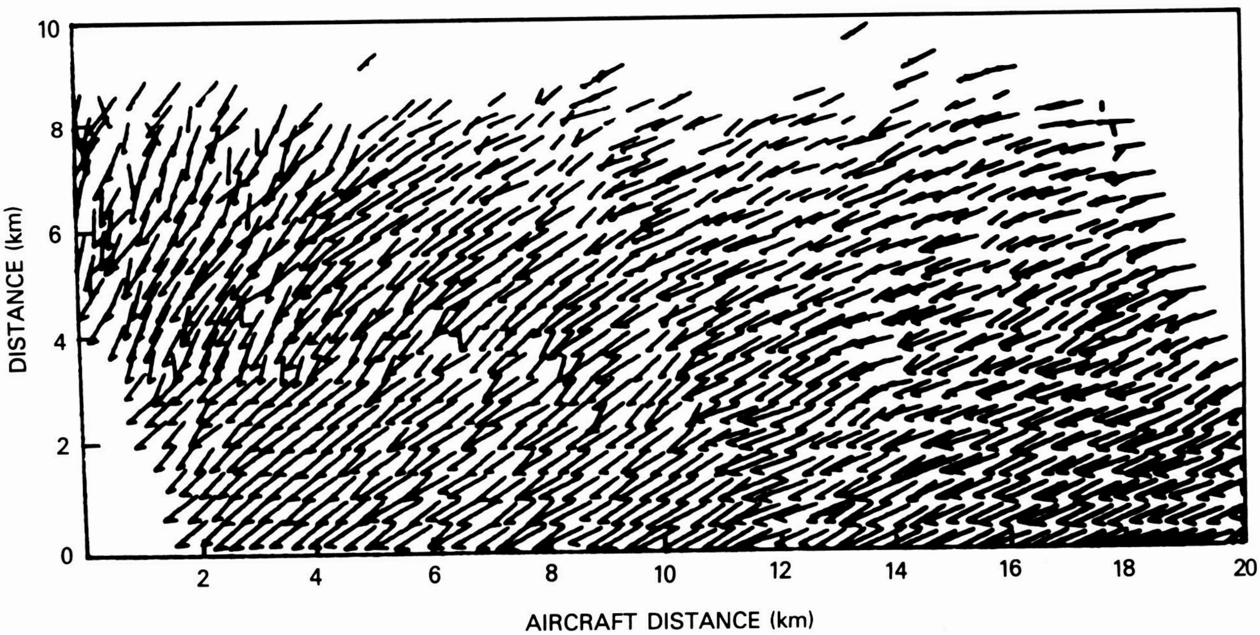

Figure 10. Real-time wind field plot from severe storm wind measurement system.

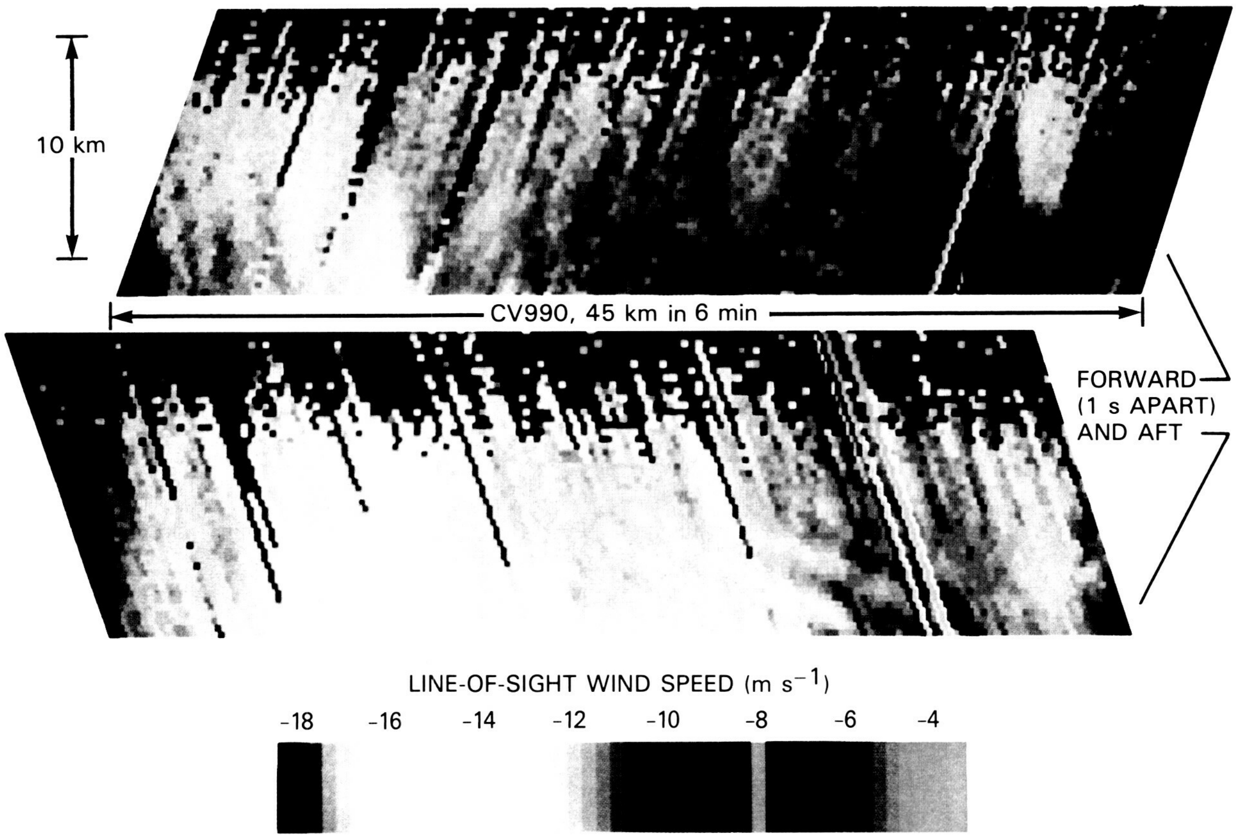

Figure 11. Color velocity display from severe storm wind measurement system line-of-sight wind speed (m s^{-1}) (California Central Valley, 500 m above ground level).

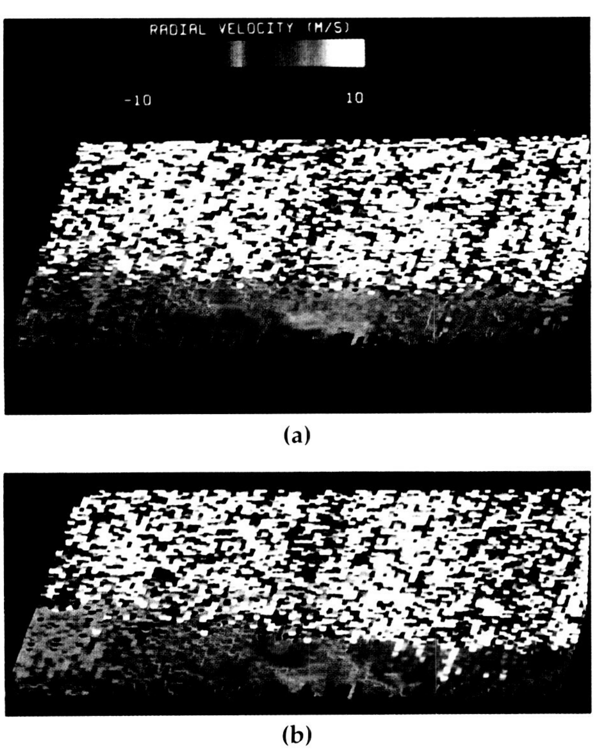

Figure 12. Color velocity displays from forward scan–1984 tests.

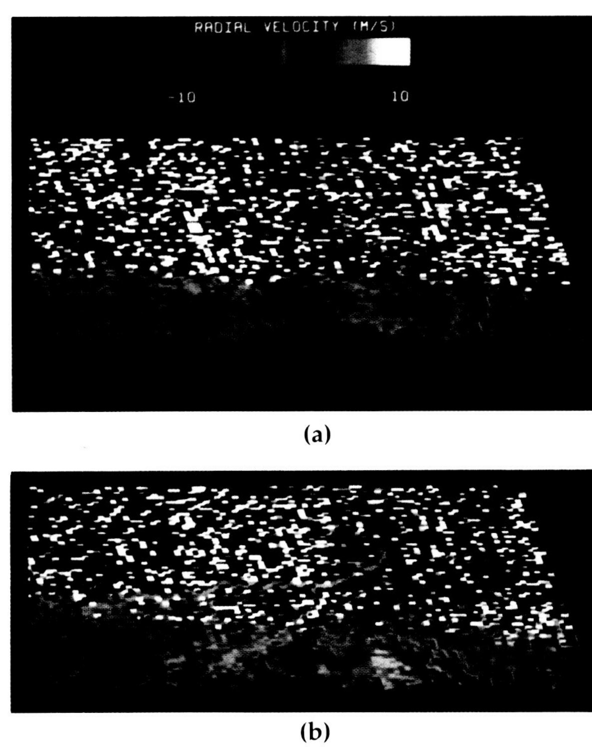

Figure 13. Color velocity displays from aft scan–1984 tests.

NEW TRANSMITTER TECHNOLOGY IN OPERATING COHERENT CO_2 LIDARS

The hybrid-TEA configuration used in the original NOAA-WPL device offers many advantages for output energies in the 100 mJ region; however, for measurements requiring output energies of 1 J or more, such a configuration does not make efficient use of the full gain region of a TEA laser. Thus, for measurements requiring higher pulse energy, unstable resonator configurations using injection-locking for frequency stabilization have been employed in recent coherent lidar systems.

The first single-frequency unstable resonator TEA transmitter for coherent lidar was developed at JPL as part of an effort to examine new technologies and produce a higher energy source for upper-level backscatter measurements (Menzies *et al.*, 1984b). The JPL transmitter is injection-controlled for SLM operation and is line tunable, producing up to 3 J of energy on the 10P(20) CO_2 line at a pulse repetition rate of 1 Hz. The lidar system has operated in both backscatter and Doppler modes. Backscatter measurements obtained from the system have demonstrated the apparent sensitivity advantage to be gained by operating a CO_2 lidar near 9.1 μm for wind measurements in the upper troposphere.

In 1985-1986, NOAA-WPL replaced the hybrid-TEA transmitter in their trailer-based system with a new 2 J, 50 Hz transmitter, based on an injection-locked unstable resonator configuration (Moody *et al.*, 1983). The system was employed in a 3-month experiment during the summer of 1986, operating relatively trouble-free over several million shots. Since the new NOAA transceiver has significant digital and automatic control features incorporated into its design, its performance and operating characteristics over the next few years should provide valuable information on lifetime and other important issues associated with development of a space-based laser system.

In addition to the research work being performed at NOAA and JPL, other injection-locked CO_2 TEA laser systems for wind and backscatter measurements are under development at AFGL in the United States and CNES/CNRS (Centre National d'Etudes Spatiales/Centre National de la Recherche Scientifique) in France. The AFGL system uses E-beam preionization, which gives better control of pulse characteristics but at a cost of increased shielding. Limited lifetime of the foil that separates the TEA gain chamber from the electron gun used for preionization is a potential reliability issue. Operation of the AFGL system should provide answers to these questions.

CO_2 LASER TECHNOLOGY WORKSHOP RECOMMENDATIONS

The problems of frequency stability and chirp were discussed at a recent NASA/RSRE workshop on closed-cycle, frequency-stable, pulsed CO_2 laser technology (Balton *et al.*, 1986).

The Panel pointed out that stability requires a correctly designed cavity having good selectivity for single-mode operation and a large spot size. The three areas of technological concern for which further research was recommended are: (1) resonator configuration, particularly with Gaussian mirrors; (2) discharge technology, including investigations of the effects of pulse injection on pulse shape and of the effectiveness of various pre-injection techniques on large volumes; and (3) improved master oscillator power amplifiers to obtain highly efficient operation without pulse distortion.

Long operational lifetime with minor-isotope CO_2 requires a catalyst that will oxidize CO to CO_2 at low temperatures while at the same time retaining isotopic integrity of the gas. Highly efficient low-temperature catalysts are currently being developed at RSRE, NASA, and elsewhere, and isotopically labeled catalysts are being developed at NASA/LaRC. The technological concerns and recommended areas of additional research are: (1) effects of catalyst-supporting materials on catalytic activity; (2) the use of promoters such as MgO in the formulation and preparation of active catalysts; (3) the development of multi-metallic metal oxide catalysts, e.g., Pt/Pd/SnO_2; and (4) the determination of oxygen exchange and co-oxidation mechanisms by stable-isotope mass spectrometry and surface analysis. In work at GEC Avionics in the United Kingdom, sealed TEA CO_2 lasers containing catalysts have demonstrated satisfactory operation for lifetimes greater than 4×10^7 pulses. *It is concluded that laser gas chemistry, which previously had set a limit to effective laser lifetime, is now no longer a limiting factor compared with other technological problems.*

As mentioned above, the main concerns with a high pulse energy, stable laser transmitter are the intrapulse frequency chirp and the pulse-to-pulse frequency stability.

The intrapulse frequency sweep or chirp is associated with a direct variation of the index of refraction, which can be due to the electronic density tail which overlaps the laser pulse (early plasma chirp)

(Flamant *et al.*, 1983; Kar *et al.*, 1985) and the heating and the subsequent motion of the lasing gas (late thermal chirp) (Willetts and Harriss, 1985), and a mismatch of the TEA-selected mode with the master oscillator frequency. The pressure shift of the CO_2 line center is about 40 to 90 kHz per torr for CO_2, depending on the line used, but N_2, He, and H_2 lead to smaller shifts of about 30 kHz per torr. CO_2 and N_2 display a blue shift whereas He and H_2 lead to a red shift (SooHoo *et al.*, 1985). A careful adjustment of the gas mixture can reduce the pressure shift between a cw or a waveguide oscillator and a high-pressure TEA CO_2 laser. The tunability provided by a waveguide laser allows injection locking at the TEA CO_2 line center.

A low plasma chirp can be provided by fast shutoff of the discharge pulse and a rapid quenching of plasma electrons. A low thermal chirp can be provided by scaling to large aperture and reducing the laser gas pressure (0.5 atm.). Reducing the pressure will reduce the GSS and delay the laser emission with respect to the discharge pulse.

VII. SPACEBORNE SYSTEM STUDIES

This chapter contains a discussion of analytical studies that define the overall requirements for a spaceborne lidar wind measuring system. Because the system requires the presence of aerosol backscatterers there is a discussion of aerosol assessment studies. Finally, hardware definition studies for a spaceborne system are described.

ANALYTICAL STUDIES OF SPACE-BASED SYSTEMS

Early analytical studies were designed to explore a broad range of considerations–lidar hardware parameters (scan rates, lag-angle compensation, pointing accuracies, etc.), satellite constraints (weight, power, stability, etc.), and meteorological effects (clouds, aerosols, turbulence, refractive index, wind shear, etc.). These "total system" studies focussed upon resolving large-scale weather patterns and providing estimates of wind vector accuracies over 300 × 300 km regions.

Following the initial simulations and their encouraging results, a series of more-detailed, computer-based studies was initiated. These studies focussed on the impact of mesoscale (~200 km) wind structures on lidar wind measurements and the development of advanced shot management and wind computation algorithms. The emphasis has been on the horizontal distribution of wind measurement uncertainties, thus providing more realistic inputs to OSSE described in Chapter III.

Total System Simulation Studies

NOAA, with U.S. Air Force-DMSP support, has studied extensively the feasibility of utilizing a satellite-borne CO_2 Doppler lidar to measure global wind profiles. Their studies analyzed the feasibility of obtaining wind measurements from both a 300 km Space Shuttle orbit and an 830 km operational orbit. A detailed computer simulation of the satellite-based lidar wind-measuring process has been developed and used to establish error limits as a function of design parameters.

The computer simulation model used in these feasibility studies included: (1) atmospheric absorption, scattering, and refractive turbulence effects; (2) meteorological parameters such as turbulence, wind shear, and clouds; (3) signal and data processing; (4) instrument characteristics for coherent detection; and (5) satellite environment and operational constraints. A scan of the specified target volume was simulated and statistically fluctuating data were obtained representing the backscatter power, radial velocity, and spectral width at each range gate within the target volume.

The geometry of the lidar system was generalized by locating the target volume relative to the satellite track. In this manner, the atmosphere of the entire globe was simulated, one volume at a time. The estimate of the wind field in this target volume was affected by lidar pointing errors, inexact satellite motion compensation, finite signal-to-noise ratio, spectral spreading caused by wind shear and turbulence, and smoothing of a nonhomogeneous wind field by least-squares data fitting. When the lidar simulation was run with realistic wind fields, an estimate of the backscatter power and the mean wind velocity (u, v, w) over the entire measuring volume was made. The rms error of this measurement ($\overline{\sigma_{\hat{u}}}$, $\overline{\sigma_{\hat{v}}}$, $\overline{\sigma_{\hat{w}}}$) was then computed to evaluate system performance.

A set of instrument parameters was selected for a Space Shuttle orbit of 300 km and a near-polar orbit of 800 km (Huffaker, 1978; Huffaker *et al.*, 1980). These parameters were selected after evaluating the TEA laser technology, Space Shuttle constraints, and navigation and pointing errors. The parameters selected for use in the computer simulation are shown in Table 6.

Table 6. Base Parameters

	Space Shuttle Orbit	Near-Polar Orbit
Altitude	300 km	830 km
Target volume (patch)	300 × 300 × 20 km	300 × 300 × 20 km
Nadir angle	62° (600 km reach)	52° (1,200 km reach)
Conical scan period	7 s	19 s
Pulse repetition frequency	8 Hz average	2 Hz average
Wavelength	9.11 μm ($^{12}C^{18}O_2$)	
Telescope diameter	1.25 m	
Pulse duration	6.7 μs	
Optical-detector efficiency	10%	
rms Long-term pointing error	50 μrad	
rms Short-term pointing error	2 μrad	
Local oscillator	50 kHz	

The results of the performance analysis for the Shuttle orbit using the lidar computer simulation of the wind measuring process are summarized in Figure 17. These results represent many computer runs for measurement volumes up to 600 km either side of the satellite ground track. A wide range of instrument and atmospheric parameters was also studied, such as wind shear, turbulence, pointing errors, local oscillator laser uncertainty, and various atmospheric models. As seen from Figure 17, the wind measurement error is less than 1 m s^{-1} throughout the troposphere.

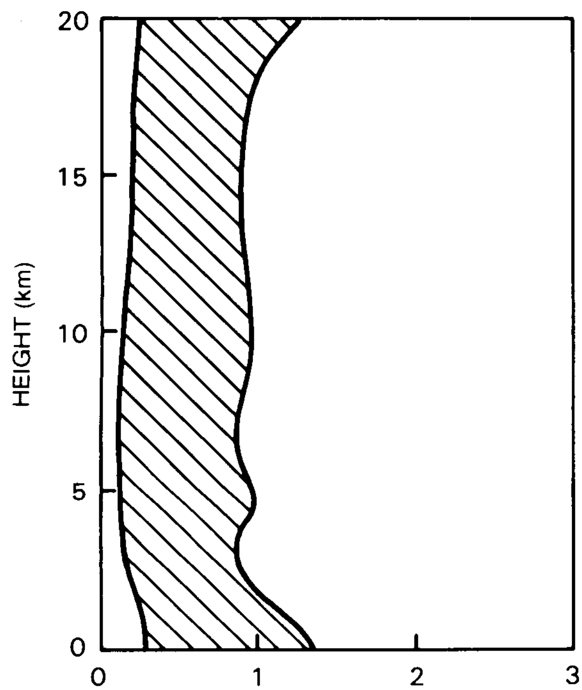

Figure 17. The range of rms wind estimate errors near 600 km either side of satellite track for a 300 km orbit (see base parameters as outlined in Table 6).

Near-Polar Orbiting Platform Studies

The analytical studies discussed above concluded that it is indeed feasible to measure the global wind field using a coherent lidar on a Space Shuttle platform in a 300 km orbit. In order to answer the question of measurement feasibility from a near-polar 830 km orbit, the base parameters were changed in the computer simulation and additional performance analysis conducted. The scan laser pulse repetition frequency was reduced to 2 Hz in order to reduce the power requirement.

Estimates of the along-track and crosstrack wind measurement error based on the base parameters are shown in Figure 18. These results indicate the feasibility of global wind profiles from an orbital height of 830 km with wind measurement error ranging from 1 m s^{-1} near ground level to approximately 5 m s^{-1} near 20 km altitude.

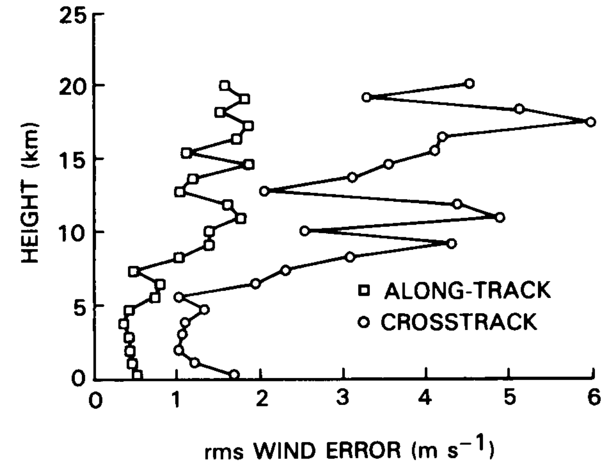

Figure 18. Along-track (a) and crosstrack (b) wind errors determined from advanced TIROS-N performance simulations (1.25 m optics, 10 J laser, 2 pps, 800 km orbit, $\beta = 3 \times 10^{-11} m^{-1} sr^{-1}$ at 10 km altitude).

Detailed Sampling Strategy and Error Analysis

Following the "total system" studies, attention was turned to a closer examination of the lidar shot pattern and the role of coherent (as opposed to random) errors in the interpretation of the lidar winds.

Current design concepts for a free-flyer Doppler lidar wind sounder employ a conical scanner with scan periods on the order of a few tens of seconds and a pulsed laser with a pulse repetition frequency (PRF) of 1 to 10 Hz. Each lidar pulse is processed to obtain a line-of-sight velocity for cylindrical sample volumes having radii of order 10 m and lengths of 0.5 to 2.0 km. A typical distribution of lidar shots through a horizontal plane at 1 km above ground level is shown in Figures 19 and 20 (Emmitt and Houston, 1986).

With an average spacing of 30 to 50 km between lidar shots, the potential for error is quite high when there are any coherent mesoscale (~100 to 1,000 km) gradients in the wind fields. These errors can be minimized if shot pairs can be found which involve line-of-sight samples sharing a common volume. Algorithms are being developed to optimize the shot pattern to obtain the best set of coincident or nearly coincident pairs of forward (of satellite position) and aft line-of-sight measurements (Emmitt, 1985a).

Figures 21 and 22 illustrate the potential for obtaining information on space scales on the order of 100 km. This simulation assumed a line-of-sight rms error of 2 m s^{-1}, a reasonable value based upon recent theoretical considerations (Menzies, 1986).

As long as laser lifetime limits the PRF and lag angle compensation limits the scanner slew rate, there will be a need to manage the available shots and to optimize their distribution pattern. Consideration

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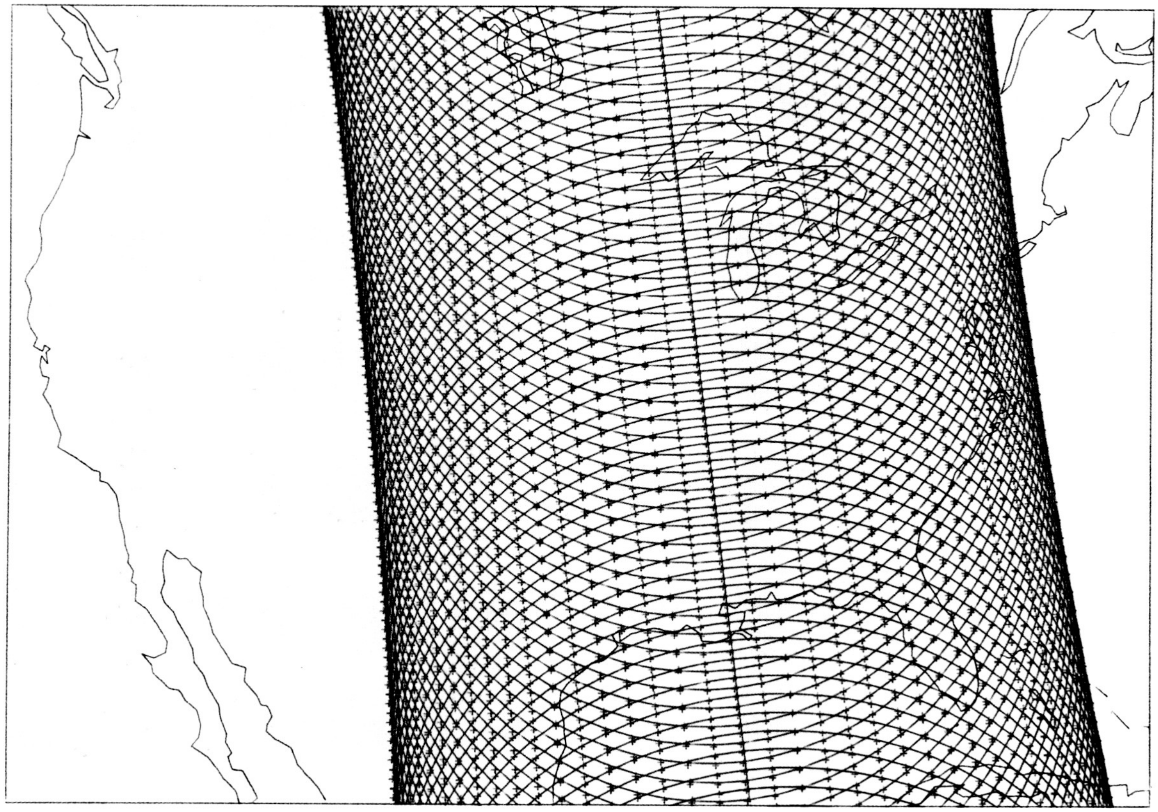

Figure 19. Example of conical scan pattern for a polar-orbiting, space-based Doppler lidar wind profiler as it passes over the Eastern U.S. The satellite height is 800 km, velocity is 7.5 km s^{-1}, scan angle = 56°, PRF = 8 s^{-1}, scan period = 10 s, and modulation amplitude = 0.33 (modulation amplitude is a function which controls the rate of rotation so that shot-pair separation is optimized).

should be given to real-time management to suppress lidar shots in some regions of the globe and to increase shot density when strong gradients are being detected.

AEROSOL ASSESSMENT STUDIES

Need for Aerosol Backscatter Data

Feasibility studies for space-based Doppler lidar wind measuring systems have shown that the accuracy of the derived wind fields will be strongly dependent on the value of the volume backscatter coefficient due to atmospheric aerosols in each lidar sample volume (Huffaker *et al.*, 1984). Feasibility studies and performance simulations for LAWS will, therefore, require global-scale information on the typical values and the spatial/temporal variability of aerosol backscatter at the prospective LAWS wavelength, and also on the spectral variability of aerosol backscatter at alternate design wavelengths.

This section reviews completed, ongoing, and planned aerosol backscatter research programs that will provide the necessary design information for LAWS. The review emphasizes a global-scale assessment of low backscatter coefficients at the 9.1 μm isotopic wavelength currently envisioned for LAWS (Huffaker *et al.*, 1984; Menzies, 1986).

Previous Work

Nearly a dozen separate research programs have involved direct measurements of aerosol backscatter at CO_2 wavelengths, with ground-based and airborne pulsed and cw lidars. A well-organized global network of ground-based pulsed lidars at shorter wavelengths has also been monitoring stratospheric aerosol events for several years.

A number of independent aerosol backscatter modeling studies have been carried out in support of LAWS. Modeling approaches involved backscatter physics, backscatter conversions from global-scale data bases of other aerosol properties, and development of global-scale backscatter composites or climatologies.

Bowdle (1986) performed the most recent comprehensive assessment of the current aerosol data base for measured and modeled aerosol backscatter coefficients at CO_2 wavelengths. This study identified a surprisingly well-defined global-scale background aerosol population. Most aerosol data bases predicted background backscatter values at 9.1 μm

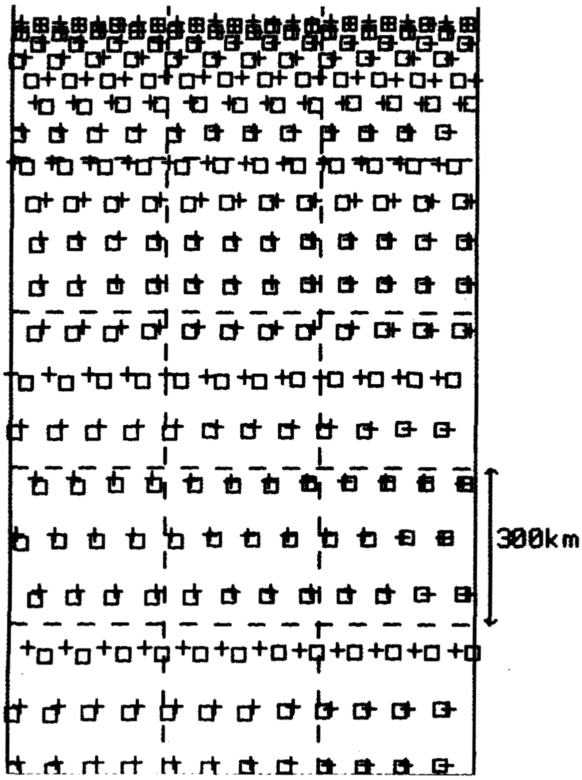

Figure 20. An enlargement of a 1,500 × 1,500 km region to the west of the satellite ground track in Figure 19. The parameters are as in Figure 19 (□ = forward shot, + = aft shot). The satellite is perceiving from left to right along the bottom of the sketch.

to be slightly larger than the projected LAWS threshold of about 10^{-10} m^{-1} sr^{-1} throughout the troposphere. Differences from one background free tropospheric data set to another usually were less than an order of magnitude, even when measurements over remote regions were compared to measurements over land. This degree of internal consistency puts reasonable bounds on the range of atmospheric backscatter values that LAWS is likely to encounter. It also reduces the scope of the assessment effort that will be required to provide an adequate global model of aerosol backscatter distributions for the LAWS development effort.

Critical uncertainties in these analyses involve the effects of sampling biases, statistical analysis methods, and conversion factors from other aerosol properties to backscatter at CO_2 wavelengths. Most of these uncertainties could result in lowering the estimated values. Backscatter estimates are periodically being updated as new data or improved conversion factors become available.

The Global Backscatter Experiment

A new 3-year aerosol study program, the Global Backscatter Experiment (GLOBE), has been developed to assess critical uncertainties in current backscatter models and to provide timely, realistic backscatter estimates for the LAWS design and development effort. The GLOBE program consists of four closely related components: (1) direct measurement of aerosol backscatter; (2) measurement of other aerosol optical and physicochemical properties; (3) modeling of aerosol backscatter properties and their global distribution; and (4) validation of measurements and models. The overall GLOBE schedule is closely coordinated with the current Eos time table. The relationships between the various GLOBE research programs are shown in Figure 23, along with the role that GLOBE will play in the LAWS design and simulation studies.

HARDWARE DEFINITION STUDIES FOR SPACE-BASED SYSTEMS

Shuttle[1]

A hardware definition study for a Space Shuttle Global Wind Profiling System was performed by the Lockheed Missiles and Space Company, with Perkin-Elmer responsible for the optics design and Sylvania for the laser design. The contract effort used the results of the NOAA analytical feasibility study. The overall objective of this study was to determine the hardware feasibility of a Space Shuttle-based feasibility demonstration system and to determine the scalability to operational conditions. The hardware study consisted of: (1) specifying the lidar system; (2) defining an operation plan and required supporting systems; (3) developing a follow-on program plan for the detailed design, development, and acquisition phases; (4) identifying long-lead items; (5) identifying and planning for required technology developments; and (6) performing a safety analysis.

In the selected design, as the Space Shuttle orbits the Earth, the telescope (1.25 m) continuously rotates about the nadir with one rotation every 7 s and a laser pulse repetition frequency of 8 s^{-1} and nadir scan angle of approximately 60°. In the recommended system an attitude-sensing system is mounted to the stationary base of the telescope providing the required laser-pointing accuracies. Because of the high telescope scan rate, the Doppler-shifted radiation returns off-axis in the diffraction-limited optical system and a lag-angle compensator is required.

The overall system configuration for measuring the global wind field in a feasibility demonstration mode on-board the Space Shuttle and using a spacelab pallet platform is shown in Figure 24.

[1]Appendix C gives a discussion of hardware definition studies that have been conducted for Shuttle-based versions of LAWS, the Shuttle Coherent Atmospheric Lidar Experiment (SCALE).

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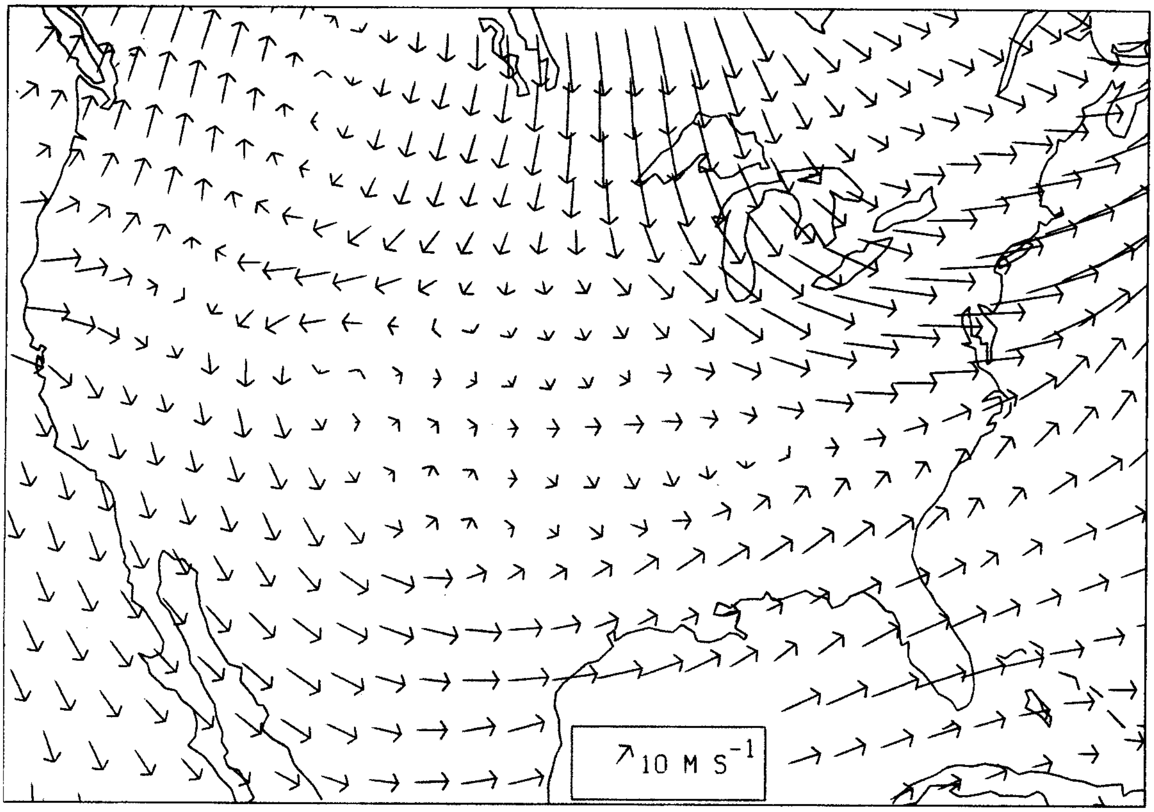


Figure 21. Input winds to computer simulation of polar-orbiting Doppler lidar wind sounder. Data taken from 500 mb wind field used as the "nature run" generated by the General Circulation Model used by the European Center for Medium Range Weather Forecasting. Wind vectors are displayed on a 1.875° latitude/longitude grid.

HARDWARE DEFINITION STUDIES FOR FREE-FLYER

A detailed study of an Eos-specific instrument has not been performed, but the results of an RCA study for an advanced TIROS-N satellite assure the feasibility of LAWS on the Eos polar platform (RCA, 1983).

Under a contract to NOAA, funded by the Air Force Space Systems Division, a study was conducted to determine the compatibility of a Coherent Lidar Global Wind Profiling System with an advanced TIROS-N spacecraft. Spectra Technologies, Incorporated (formerly, Mathematical Sciences Northwest) was subcontractor for the laser design and Perkin-Elmer Corporation for the optical system design. Results of this study indicated that the coherent lidar power and weight requirements were within the Eos polar platform capabilities.

The primary conclusions of this study were that an advanced TIROS-N satellite could meet the operational requirements of the coherent lidar instrument for longer than 2 years (Altman *et al.*, 1983) (Figure 25).

NASA's Marshall Space Flight Center completed in 1982 (Park, 1982) a feasibility assessment of space-based operation of a Doppler lidar wind measuring system. This study extended NOAA's work to include free flyer operation. The assessment concentrated on key aspects in three areas which were considered vital to the feasibility of the concept. These were: (1) lidar system hardware; (2) atmospheric effects; and (3) spacecraft accommodations. The baseline system used in the assessment was the Shuttle system described by the Lockheed Missiles and Space Corporation "Windsat" study (LMSC, 1981). Support to this study was provided by the Jet Propulsion Laboratory, Langley Research Center, and Goddard Space Flight Center. The conclusions of this study were:

- A reliable model of backscatter profiles with altitude at the specific wavelength of the lidar is needed.
- A global model of the atmospheric aerosol content should be developed.
- The optimum laser configuration having the required lifetime must be determined.

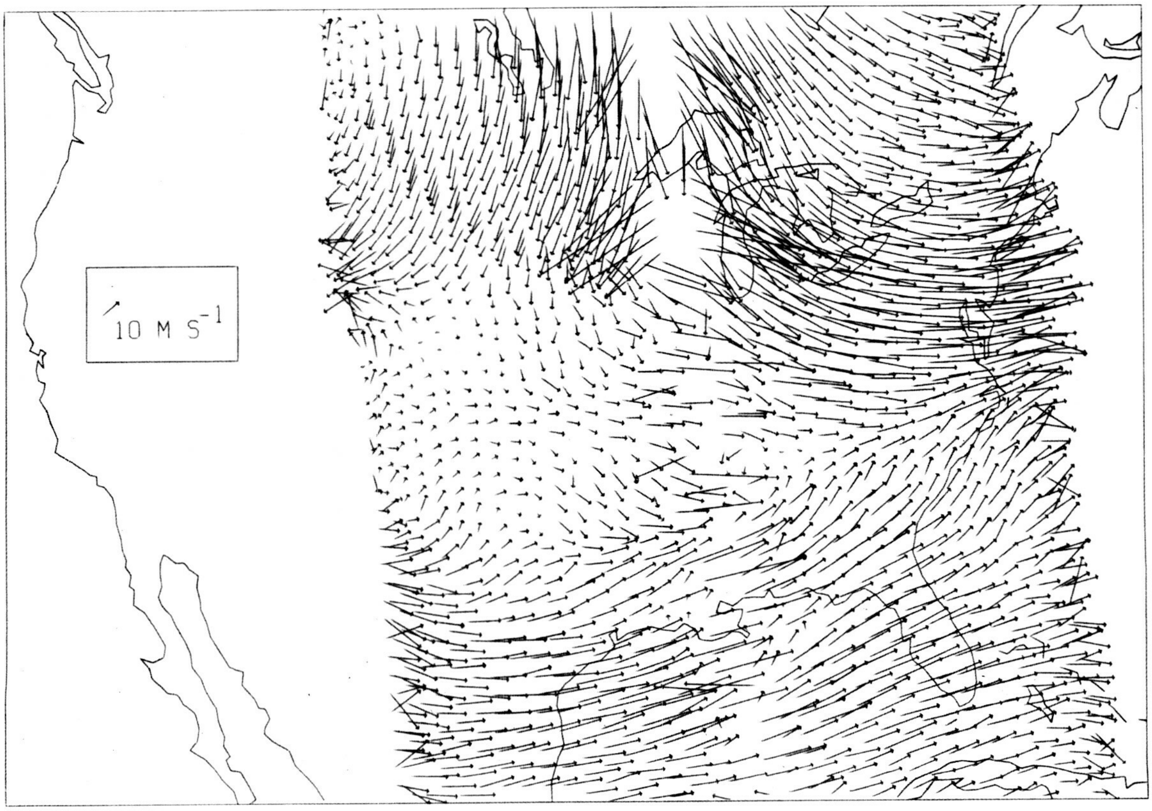


Figure 22. Output winds from computer simulation using the data in Figure 21. Spacing of the wind vectors is variable and depends upon the lidar shot pattern. Vectors displayed are only those obtained from the "first order" pairs–i.e., the best combination of line-of-sight winds within 10 × 10 km zones.

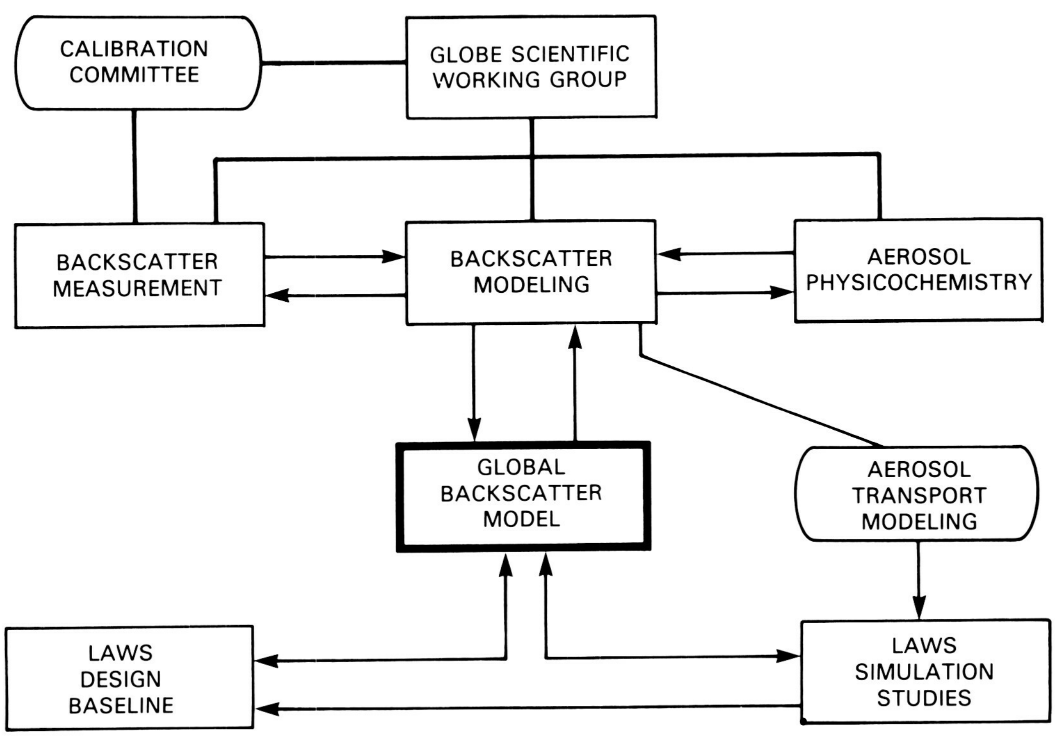


Figure 23. Relationship of GLOBE to the LAWS development.

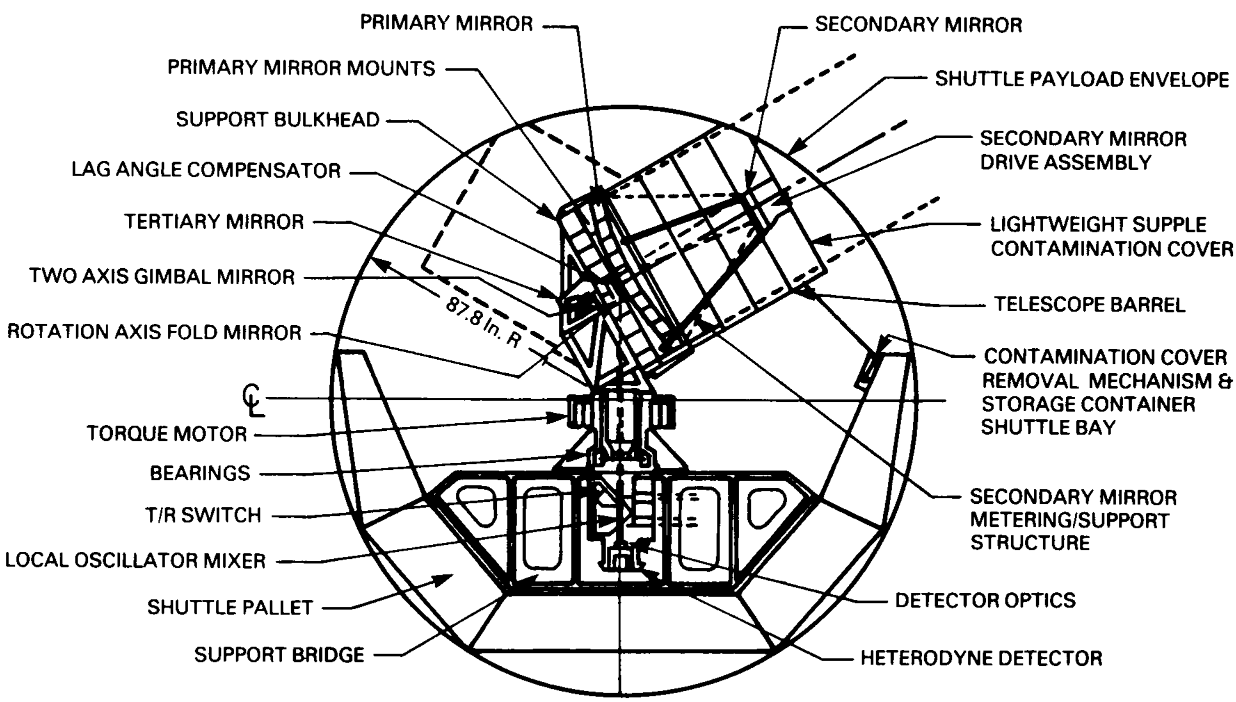


Figure 24. Side view of recommended lidar design mounted on the Space Shuttle pallet.

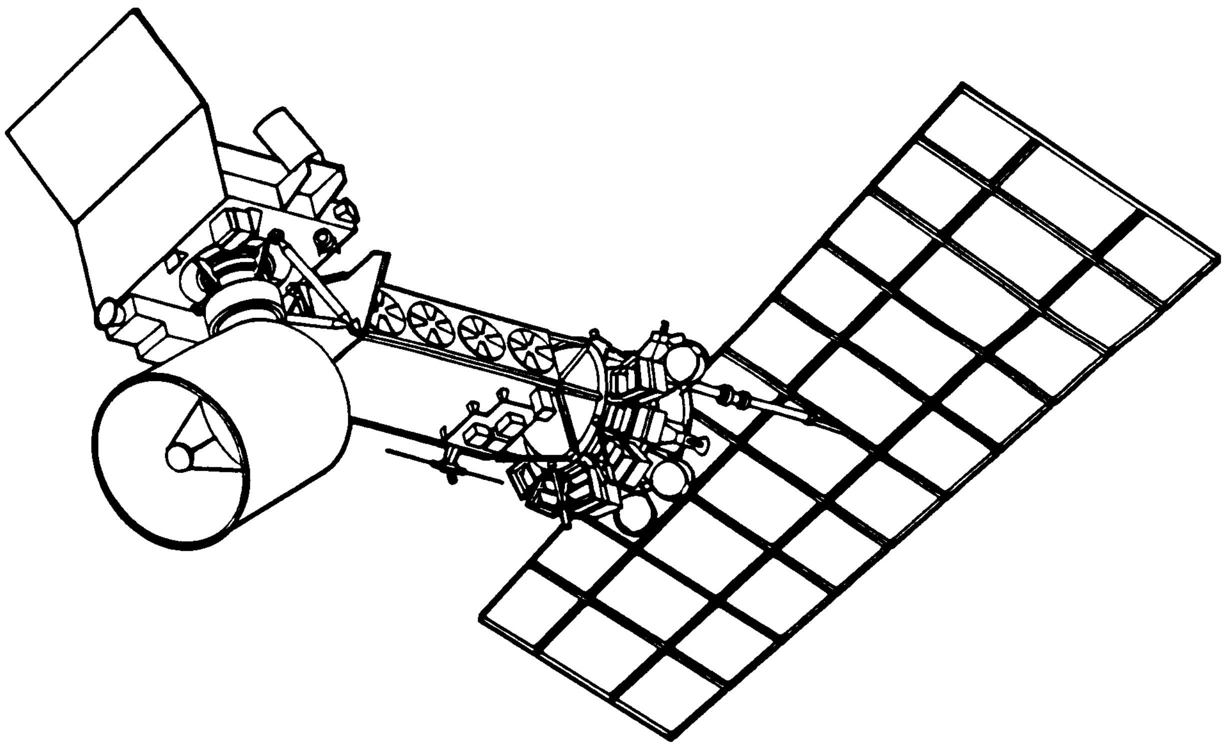


Figure 25. Windsat free flyer.

Space Station System

A study is being conducted of a LAWS system on Space Station. The basic assumptions for this study are: 10 J laser capable of 10^9 shots, 1.5 m scanning telescope, and 500 km platform altitude. The threshold sensitivity of the system to atmospheric backscatter as a function of nadir angle is shown in Figure 26. More detailed accommodation studies are in progress. An artist's concept for Space Station attachment is shown in Figure 27.

In summary, preliminary results of hardware studies, in progress, assure the feasibility of LAWS on a space platform. Since an assessment of the global and seasonal variation of atmospheric backscatter is crucial to the hardware design, a Global Aerosol Experiment (GLOBE) has been initiated. Preliminary results of this aerosol assessment indicate backscatter of sufficient magnitude to be consistent with present system designs. Analytical studies have guided the development of optimum scan geometries necessary for efficient sampling strategies and have shown that the total system will achieve the required wind velocity estimate accuracies.

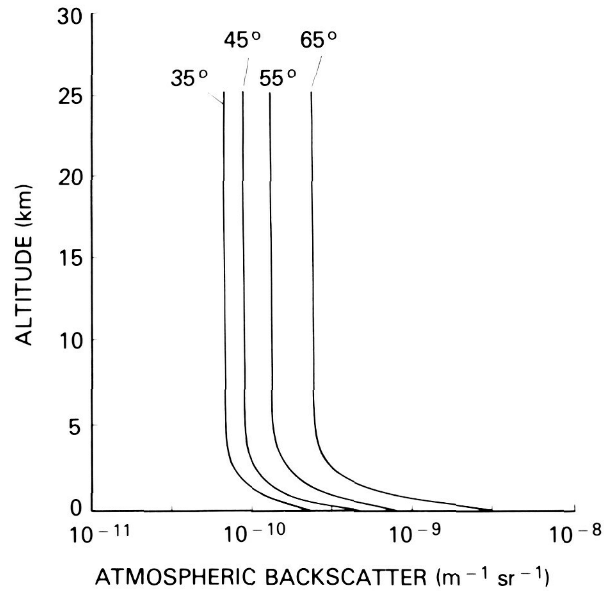


Figure 26. Backscatter intensity as a function of nadir angle for Space Station operation.

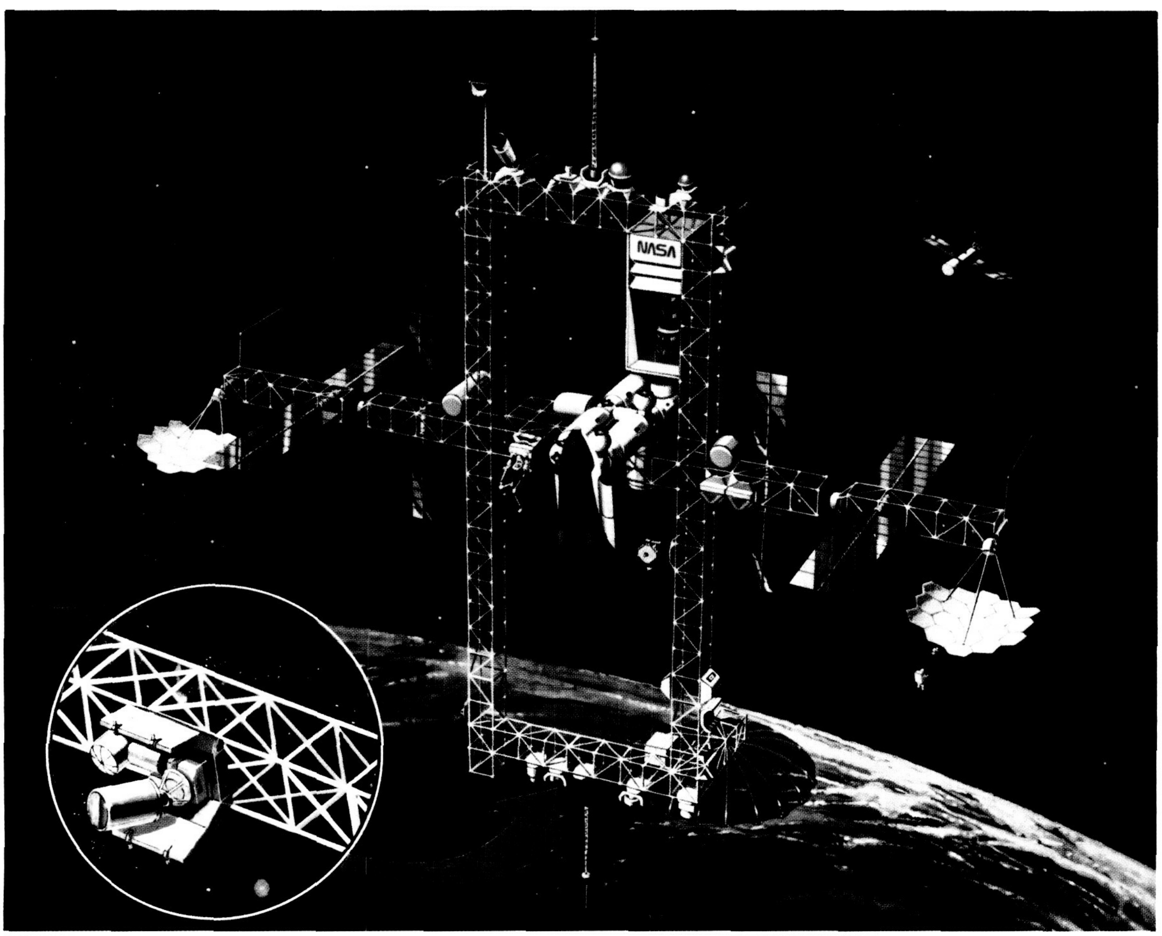


Figure 27. LAWS as an attached Space Station payload.

VIII. LASER ATMOSPHERIC WIND SOUNDER DATA MANAGEMENT

INTRODUCTION

A primary part of the entire Eos concept is the data system to serve interdisciplinary Earth systems studies. Global wind profile data from a LAWS instrument will be a part of many such investigations and will eventually help operational weather forecasting. Thus, it is imperative that the data management aspects of LAWS be compatible with the Eos data and information system itself. As will be the case for other Eos instruments, the LAWS data system must be designed to serve a wide variety of uses, from climate research to near real-time forecasting. The LAWS instrument will also have unique attributes that must be taken into account when designing the data system. For example, the winds obtained from a LAWS instrument must be calculated from small-scale, line-of-sight measurements taken from different angles as the spacecraft passes overhead. This chapter will discuss the LAWS data system and the three most important issues: users, compatibility, and uniqueness requirements.

Users

Four types of data users are delineated in the report of the Eos Data Panel (Chase *et al.*, 1985). All four groups will be major users of the LAWS wind data, and their needs must be accommodated. Needing real-time or near real-time data are the first two types of users, namely, the instrument team members in control of experiment hardware and scientists involved with nowcasting or forecasting. The other types of users listed in the Eos Data Panel Report will get their data from the Eos mission data base, with the difference being that one group will specify particular times or geographical locations, while the other group are browsers, looking through the data for particular features, attributes, or special cases. As far as the LAWS instrument data system goes, these last two user groups are the same. All instrument-specific data must be saved so that these users can find what they need. For example, the instrument signal-to-noise ratio, or other data quality information must be available to allow researchers to apply meaningful error tolerances.

Compatibility

To discuss the compatibility requirements of Eos it is necessary to briefly recall the different levels of data processing defined in the Eos Data Panel Report.

Level 0 – Reconstructed unprocessed instrument data at full resolution. This may be raw data from an optical detector, processed data from an on-board signal processor, or a combination of both. For example, if lower levels of processing are used, various types of Fourier schemes could be tried *post facto* to get more signal out of the noise.

Level 1A – The same as Level 0 with ancillary information appended, such as calibrations, georeferencing information, platform ephemeris, etc. This is the lowest level which is a complete data set.

Level 1B – The same as Level 1A processed to sensor units. In the case of LAWS this should include the Fourier processing or whatever else is necessary to obtain velocities out of the raw instrument data. Platform motion and position should be taken into account to provide line-of-sight velocity relative to the Earth versus height above ground. This is the highest level data set that is reversible, so no averaging or other irreversible processing can be used. This data set will be archived to allow alternative Level 2 processing.

Level 2 – Derived meteorological variables, in this case, wind profiles. Line-of-sight velocities must be averaged together in some fashion to yield winds, i.e., vector components of the horizontal velocity. The averaging process produces actual wind profiles and estimates of their quality. These profiles can then be processed into a suitable Level 2 format (WMO, 1986) for archival and distribution for use in data assimilation and diagnostic studies.

To minimize the amount of data processing required by the data users, the Level 2 format must be strictly followed. It is recommended that a specific group be assigned responsibility for routine Level 2 production and archival to ensure consistent data quality and ready availability. Simulated wind profile reports now being produced for use in observing system simulation experiments could be utilized to test Level 2 software. Horizontal spatial resolution will depend on the way that the averaging is done. This is an irreversible step, and, also should be distinguished from the Level 3 processing which may involve the blending of several Level 2 data sets. Assumptions must be made about vertical velocities, and there may be other ways in which these data depend on the processing method. At this level the data are still in swaths corresponding to the individual orbits. This is the highest level at which the LAWS data system should be concerned.

Even though there is considerable processing to achieve this level, it should be available in near real-time since these are the data that will be of most use to field programs, and later to NOAA when they are ready to accommodate the data in their operational analysis/forecast system.

Level 3 – Interpolated and mosaicked data from a data assimilation system. Through the assimilation process the wind data from LAWS can be blended with other measurements such as from rawinsondes and aircraft. Derived quantities (Level 4) such as vertical velocities or diabatic heating will be computed from the combined assimilated data set that includes the winds. Alternatively, wind values can be combined from nearby orbits without the use of a model to construct wind fields over a larger region. Data Levels 3 and 4 need not be the responsibility of the LAWS investigation team, but are essential for a variety of Eos science requirements.

Uniqueness

The LAWS instrument will be different from the more conventional methods of measuring the wind and from other Eos instruments. Details will depend on the exact hardware configuration that is selected, but there are a number of common attributes to consider. The instrument, as described above, will measure the range-resolved line-of-sight velocity along the laser beam. The cross section itself will be quite small, only tens of meters in the case of coherent Doppler lidar. A large number of measurements must be combined to form a horizontal wind vector that can be used in global modeling.

In contrast with other remote instruments, such as passive infrared temperature sounders, measurement of velocity by LAWS will be direct: aerosol particles that actually move with the air are being sensed, but the movement recorded is not the same vector that is ordinarily used. In the LAWS instrument, air motion is obtained relatively easily and unambiguously, but must be processed to obtain the wind.

Different users of wind data will have different requirements for products from the LAWS data system. Researchers interested in mesoscale winds will want to use the data at the highest resolution, Level 1B. Some researchers may want only the Level 2 data for use in global modeling, but others will want to do the averaging themselves for some special purposes. The requirements of operational forecasting will eventually compel the LAWS data system to provide Level 2 data in near real-time.

DATA SYSTEM DISCUSSION

The following aspects of the LAWS data system require further discussion.

Data Rates

We will assume that at least part of the data is transmitted down in raw form, so that alternative methods to obtain the mean frequency of the Doppler-shifted signal can be tried. On-board processing can, of course, be used to lower the data rates and may be the best course to pursue for operational use. For research work, however, there is no substitute for the raw data. To give an idea of the raw data rates, we will use the example of a Doppler lidar, operating at approximately 10 μm. To be able to measure 100 m s^{-1} either side of the center frequency, 22 MHz each is needed for the real and quadrature parts of the signal. Sampling twice per wave gives a total of 88 MHz of 8 bit data, but the duty cycle is very low. The pulse rate will only be approximately 10 Hz and the amount of data sampled only about 15 km (50 μs), so the net raw data rate is less than 1 Mbit/s, much less than that of several other candidate Eos instruments. If an on-board processor is used, the amount of data will be very small, only a few spectral moments per range gate and 15 range gates through the troposphere, so the net is less than 4 kbits/s. As mentioned above, access to the raw data will be necessary for research on spectral techniques. It should be possible to retain all the raw data for conversion to Level 1 data for archiving. When the conversion to Level 1A data is accomplished, the Level 0 data can be discarded.

Computation of the u and v Components

The line-of-sight winds computed during processing Level 1B must be combined in some manner to obtain estimates of the u and v components of the sampled wind field (Emmitt, 1985b). Whether this level of processing takes place on the satellite or only after data transmission depends upon on-board scanning management requirements and real-time user demands. However, since Level 2 processing is usually irreversible, it will be necessary to transmit the lower level data for ground-based computations regardless of Level 2 requirements.

On-board processing of u and v components may be desirable if lidar shot management is to be optimized for laser lifetime, dynamic sampling based upon real-time gradient detection, and cloud tracking support. Algorithms for these tasks may be quite different and less complex than those used to produce

Level 2 data for ground-based use and may vary significantly depending upon the lidar hardware configuration.

In all instances, on-board or ground-based computations of u and v components will require the following ancillary data: shot geometry–i.e., shot angles; signal-to-noise ratios for each line-of-sight velocity measurement; and platform georeferencing and ephemeris.

These data are used to weight the information obtained from each shot and to provide the basis for optimum pairing of line-of-sight measurements to obtain area-averaged u and v wind vectors.

The amount of averaging will depend upon the user. The accuracy of the computed wind speed will increase with an increase in averaging area and shot density while the representativeness of the wind estimate may decrease in regions of coherent wind structure (jets, sea breezes, etc.). For these reasons it is desirable to do as little averaging as possible and provide the finest scale u and v data along with the necessary quality indicators.

IX. CONCEPT AND STRATEGY FOR DEVELOPING A SPACE-BASED WIND PROFILER

SYSTEM CONCEPT

On the basis of the foregoing discussions, it is concluded that the development of a Laser Atmospheric Wind Sounder is both timely and feasible. Of the possibilities that have been considered, a coherent lidar system based on pulsed CO_2 laser technology at 9 μm is considered at the present time to be the most promising.

The system concept thus envisages Doppler measurement of line-of-sight wind components from aerosol backscattering in the atmosphere. With a conically scanned optical arrangement, successive measurements from different directions will provide global coverage of wind profiles throughout the troposphere, on a spatial scale of 100 km at 1 km height intervals, and with an expected accuracy better than 1 m s^{-1}. Precise shot management should allow for more detailed interrogation of fine-scale meteorological features. By reasonable extrapolation of present technology, a working lifetime in orbit of at least 2 years may be anticipated for an operational system. There are no eye safety hazards.

An evolutionary development strategy, prospects for international cooperation, and technology points for immediate study and development are outlined below.

DEVELOPMENT STRATEGY

To achieve the capability of global wind profile measurements, a chronological progression for LAWS is envisioned, which logically addresses the technological uncertainties remaining. The most serious uncertainties impeding the development of CO_2 coherent Doppler lidar systems for space applications are the following: (1) insufficient knowledge of the absolute magnitude and variability of the atmospheric backscatter at the wavelengths of interest; (2) design of a laser system with the highest efficiency possible; (3) design of a pulsed laser system with sufficient output power ($\sim$10 J/pulse) and with the required frequency stability; and (4) design of a laser system with sufficient lifetime to permit unattended operation for a 1- to 2-year period ($\sim 10^8$ shots).

To better understand the distribution of aerosol backscatter, a Global Aerosol Backscatter Experiment (GLOBE) has been initiated through the sponsorship of NASA's Global Scale Atmospheric Processes Research Program. The goal of this effort is to observe the geographic and seasonal variability of aerosol backscatter through a combination of ground-based, airborne, and satellite measurements. The result of this experiment will be a physical model of the backscatter variations, based on the observations and our accumulated knowledge of aerosol physics. The model will be used to determine the frequency, magnitude, location, and meteorological situation of the smallest backscatter values. These results will be used in the lidar system design to determine the laser power and telescope aperture required to achieve adequate signal-to-noise.

Laser technology issues are presently being addressed within NASA and elsewhere. One of these, the development of chemical exchange techniques using catalysts to extend the lifetimes of CO_2 laser operation, was the subject of a 1986 joint conference between RSRE of the United Kingdom and NASA. Because there is mutual interest and need for the development of these catalyst techniques by the governments of both nations, the conference recommended continued collaboration in the development and test of these techniques. An additional topic addressed at the joint conference was the development of techniques needed to produce the high frequency stability required by coherent Doppler systems subject to the difficulties of high pulse power and long lifetime. This latter area, frequency stability, will also be an area of joint study.

We believe that the work in progress in these areas will lay a firm foundation for the preparation of designs for a spaceborne Doppler lidar system. The ultimate goal of all these efforts is the measurement of global wind profiles from polar orbit. If necessary, a long-duration Space Station flight would allow issues of laser lifetime to be studied in an environment of virtually continuous on-orbit access to the instrument. During such a flight considerable scientific results could be obtained, since the altitude and inclination of the manned Space Station will allow almost complete coverage of the tropics. Wind profile data, even if restricted to this area of the globe, would open entire new avenues to research in tropical meteorology and in the effect of the tropics on the climate of the rest of the globe.

The ultimate goal of the LAWS effort will be the deployment and use of a Doppler lidar wind profiler on one or more of the Eos polar-orbiting platforms. Continuous application of this instrumentation over a period of several years will provide global data, for research and eventually for operational needs, of quality far superior to any satellite data now available. It has been estimated that these wind profile data will extend the accuracy and duration of weather forecasting skill dramatically.

INTERNATIONAL COOPERATION

Over the past year, an ESA working group on Space Laser Sounding and Ranging has been conducting an extensive study of laser systems in space. This working group is due to report early in 1987; its recommendations are likely to include strong support for a program leading to the development of a laser global wind profiler. Taking account of the strength of relevant laser, detector, and optical technology in Europe, there is a strong case for considerable international cooperation. Such cooperation could include initial interchange of modeling and design parameters, leading eventually to joint component, subsystem, and system development.

On the user side it is important to involve the meteorological offices of various nations. This includes not only Europe, but also those countries close to the equator, notably Brazil, India, China, and Australia for which wind information will have considerable impact.

TECHNOLOGY DEVELOPMENT

The essential components of a global wind profile lidar program include the laser, the optics, the scanning system, detection and signal processing, and data handling and transfer. As previous discussions have pointed out, the basic technology for the construction of a spaceborne CO_2 lidar is in existence. There are, however, specific areas where further development should take place to ensure a high degree of success and reduce overall risk. This section highlights the areas where further development should be concentrated. In general, the operational issues of space qualification, lifetime, reliability, mass, volume, and power consumption must all be dealt with in the course of a development program.

Chapter V has addressed the areas of laser development which need additional effort, namely, lifetime, reliability, and stability. Various design configurations need to be more closely examined and brass-board versions constructed of viable candidates.

For the optics, important questions concern the construction and operation of a large (up to 1.5 m diameter) scanning telescope system. In particular, pointing and scanning stability and lag-angle compensation must be addressed.

The remaining developmental areas are those that would occur normally in the course of a system development program and are therefore not discussed here.

APPENDIX A: CORRESPONDENCE FROM BONNER

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE
National Meteorological Center
Washington, D.C. 20233

July 24, 1986 W/NMC:WDB

Dr. Robert J. Curran
National Aeronautics and Space Adm.
Code EE
Washington, DC 20546

Dear Dr. Curran:

This letter is a reply to your question concerning the value attributed by the National Meteorological Center to global wind profiles.

Experience at the National Meteorological Center has convinced forecasters that, given the swath size in which polar-orbiting satellite data becomes available to the forecast operation, the addition of global wind profiles offers the best opportunity for significant improvement in medium and large-scale forecasts. Stated another way, global wind profiles are, we feel, relatively more desirable than either more, or more accurate, temperature profiles.

I do not mean that the need for soundings has diminished. Our interest continues in all-weather soundings, and sounding data with usable signal levels from smaller fields of view. For such mesoscale uses as forecaster support for severe storm forecasts, we have a substantial interest in geostationary cloud-penetrating soundings, especially for the area of the continental United States.

However, given the forecast-model's tendency in certain situations which frequently occur, to accept wind data in preference to sounding data, our conviction is that wind data will enhance forecasts on all scales. This is especially true for low-latitude regions, were measurement of pressure-surface heights by direct or remote-sensing means is virtually impossible.

I hope this reply will be useful to you in your planning for future satellite instruments.

Sincerely,

William D. Bonner
Director
National Meteorological Center

cc:
D. Fitzjarrald, MSFC, ED43
W. Baker, GSFC, Code 611
J. Sparkman, NESDIS, E/SPD-1

APPENDIX B: CORRESPONDENCE FROM BENGTSSON

LASER ATMOSPHERIC WIND SOUNDER

The use of space-based observing platforms is, and will continue to be, the only way to produce three-dimensional information on a global and continuous basis. The importance of such remotely observed data for operational weather forecasting and climate studies cannot be overestimated.

Although the temperature and humidity data produced from the radiance measurements obtained from the present generation of satellites are invaluable, it is well proven that the addition of accurate wind data for the globe would improve the analysis of both the three-dimensional atmospheric wind and temperature fields. This in turn would lead directly to improvements in operational weather forecasting and in our knowledge of the General Circulation, and eventually, through diagnostic studies, to improved models of the atmosphere.

Over the next ten years the trend will be for increased resolution in global and regional models and consequently there will be a requirement for accurate high resolution analyses of the temperature and wind field. For fairly large horizontal length-scales the mid latitude wind field can be inferred from the temperature field from dynamical balance considerations; however, for short horizontal scales and the tropical region, high resolution wind observations are a pre-requisite for good analyses. In addition, it is clear that improvements in the analyses and forecasts for the southern hemisphere will only come when the observing network is improved significantly.

The report from the LAWS panel is timely, since the requirement is proven and technology for a laser sounder appears to be feasible.

Lennart Bengtsson
Director, ECMWF

APPENDIX C: HARDWARE DEFINITION STUDY OF A SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

A study was performed by NASA/MSFC in 1985 (Bilbro *et al.*, 1987) for a Space Shuttle experiment which had as its primary goals: (1) to define the requirements for a Doppler lidar flight experiment on a shuttle/spacelab mission, and (2) to fly a shuttle mission to measure winds and aerosol backscatter from space.

This study, referred to as the Shuttle Coherent Atmospheric Lidar Experiment (SCALE), was undertaken specifically to determine what could be done using existing technology; therefore, the lidar was based around the 2 J laser built for NOAA by Spectra Technologies, Inc. The study included: (1) a detailed space qualification study of the laser design; (2) a preliminary optics and telescope design; (3) an accommodation study, which addressed power, weight, thermal, and control system requirements; and (4) a flight trajectory study and operations plan study designed to accomplish the required scientific and engineering goals.

The system parameters for SCALE are shown in Table C.1. The sensitivity based on these parameters is shown as a function of different atmospheric conditions in Figure C.1. Using the calculated sensitivity and a measured backscatter profile, the radial velocity error shown in Figure C.2 was produced. The specific laser parameters are 2 J energy, 25 Hz pulse repetition frequency, 5 μs pulse, 3 percent wallplug efficiency, and 10^7 pulse lifetime. This is an existing proven design based on isotopic operation and is nonrecycling. The telescope parameters are given in Table C.2. The optical layout and mechanical configuration are shown in Figures C.3 and C.4. The overall configuration is shown in Figure C.5 mounted on a spacelab pallet. An artist's concept of

Table C.1. SCALE System Parameters

Laser	**Focal Plane**	
2 J pulse energy	HgCdTe detector	
25 Hz repetition rate	Cryogenic cooled	
5 μs pulse duration	Shuttle motion corrected	
9.11 μm wavelength	**Signal Processing**	
10^7 shot lifetime		
Non-recycling operation	On-board FFT processing	
	Real-time data transfer	
Optics		
1.25 m aperture	**Power Requirements** (W)	
Diffraction limited		
Fixed pointing	Laser	1,375
Lag-angle compensated	Focal plane	38
	Signal processing	186
Pointing	Support structure	26
Shuttle accuracy (±.50°)	Cooling	315
		2,040

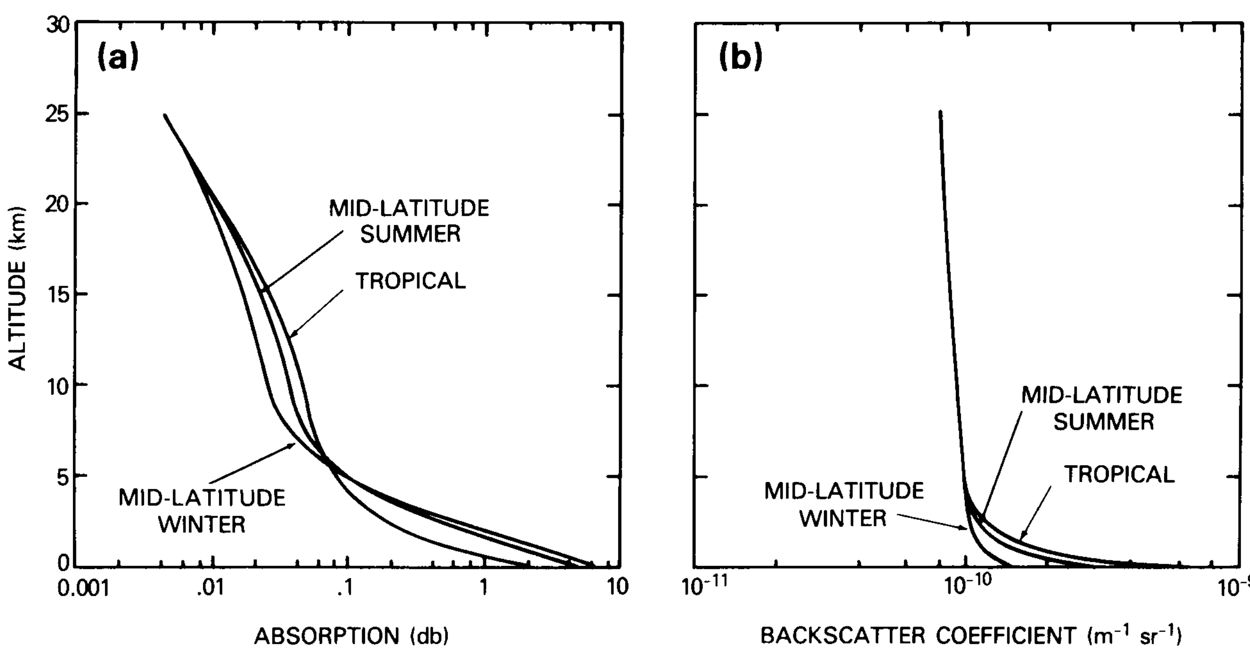


Figure C.1. SCALE sensitivity at 9.11 μm. (a) Absorption measured at 45° from nadir. (b) Backscatter for an 185 km orbit, 45° from nadir (includes aerosol extinction from Haze C model).

the system is shown in Figure C.6. The results from this study are as follows:

- SCALE has been designed based on an existing operational pulsed CO_2 laser.
- Space qualification studies have shown that there are no significant problems involved in qualifying the laser for Shuttle flight.
- Accommodation studies have shown that there are no significant problems involved in accommodating the experiment.
- System sensitivity studies have shown that valuable scientific information can be obtained relative to the global distribution of atmospheric backscatter at 9.11 μm.
- Significant scientific information can be obtained from space-based wind measurements.

Using the radial (or line of sight) velocity errors in Figure C.2 further simulations were done (Emmitt and Houston, 1985) to assess the impact that the SCALE sampling mode would have on the computation of the horizontal wind vectors. Figure C.7 illustrates the cycloidal shot pattern and the resulting vectors for a specific input wind field. The uncertainties are large along most of the shot track except at the cusp of the cycloid where the lidar dwells for a few seconds providing greater shot density and several shot perspectives.

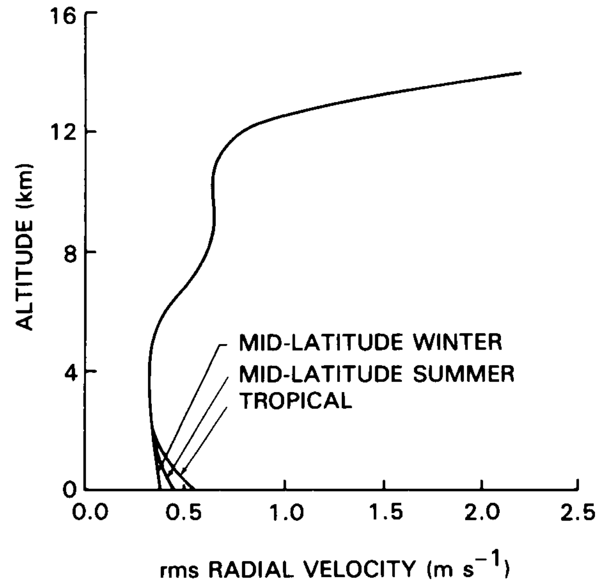


Figure C.2. Radial velocity error for 9.11 μm (185 km orbit, 45° from nadir).

Table C.2. SCALE Telescope Parameters*

Primary diameter	125 cm
Primary vertex radius	–400 cm
Primary figure	Paraboloid
Secondary diameter	6.25 cm
Secondary vertex radius	–20 cm
Secondary figure	Paraboloid
Primary/secondary separation	190 cm
Secondary magnification	20
Surface roughness	$< \lambda/5$ at 6,328 Å
Tilt	1.9 μrad decollimization per milliradian tilt
Decenter	1.9 μrad decollimization per 0.1 mm decenter
Despace	2.2 μrad decollimization per micrometer despace
Maximum expected lag angle in object space	0.11 cm
Maximum expected lag angle in image space	2.2 mrad
Fixed pointing	

*Afocal Cassegrain, diamond-turned aluminum, gold coated

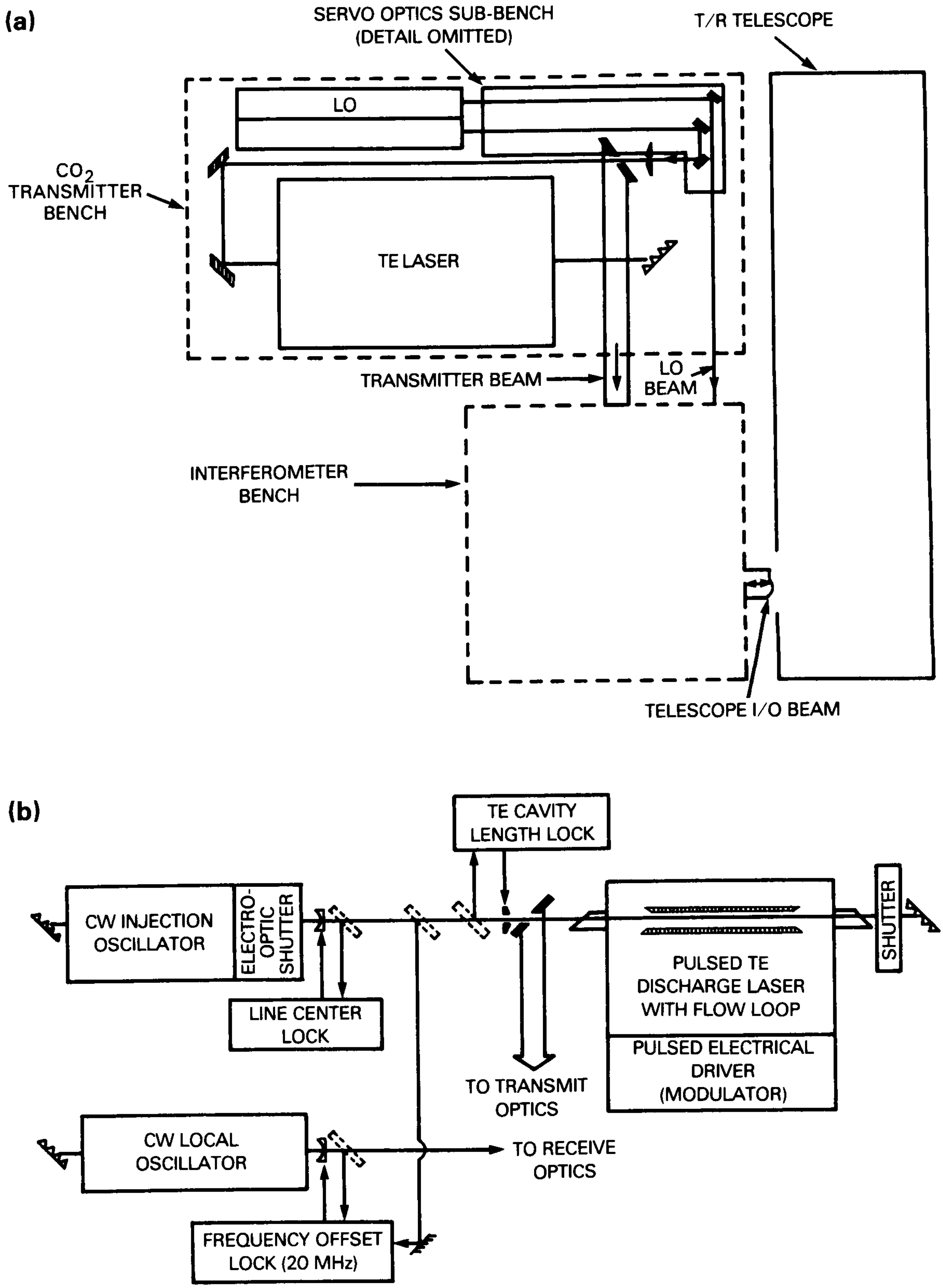
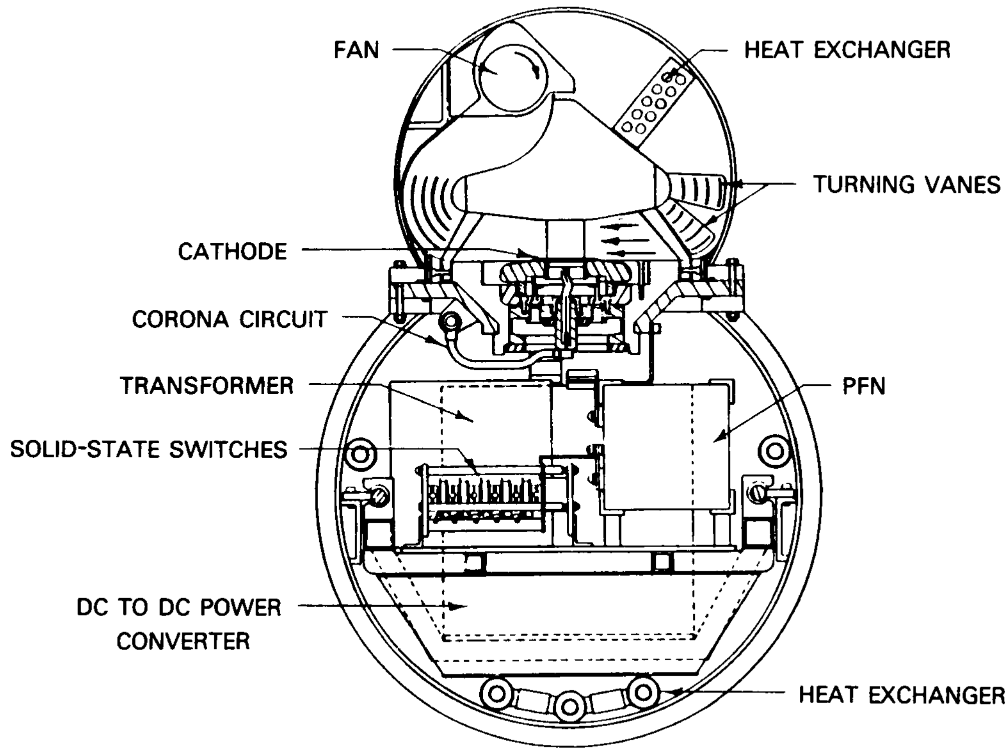


Figure C.3. SCALE schematics. (a) Optical layout. (b) Conceptual design for the high-average-power lidar upgrade.

(a)



(b)

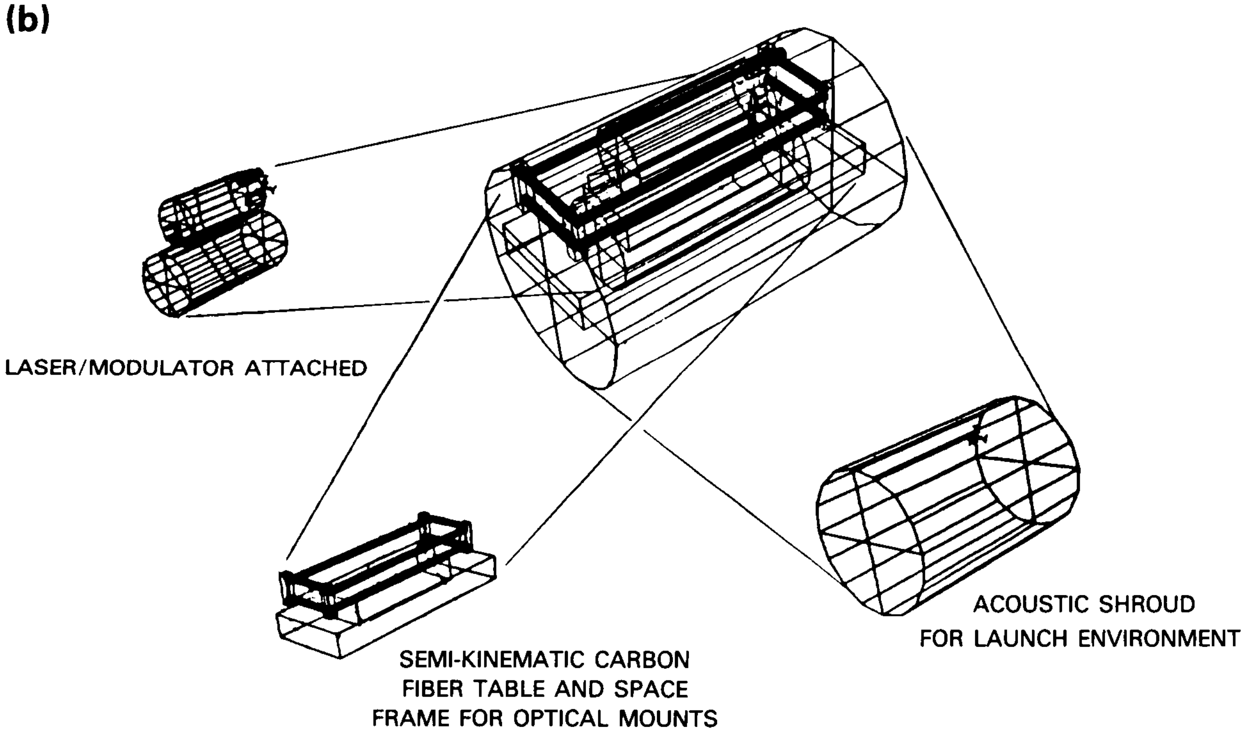


Figure C.4. Cross-sectional drawing of the laser head and modulator (a) and structural configuration (b) of the high-average-power lidar upgrade. Laser weight ~495 lbs and volume ~44 ft³ (16 in. diameter × 38 in.). Modulator weight ~1,000 lbs and volume ~8.5 ft³ (22 in. diameter × 38 in.).

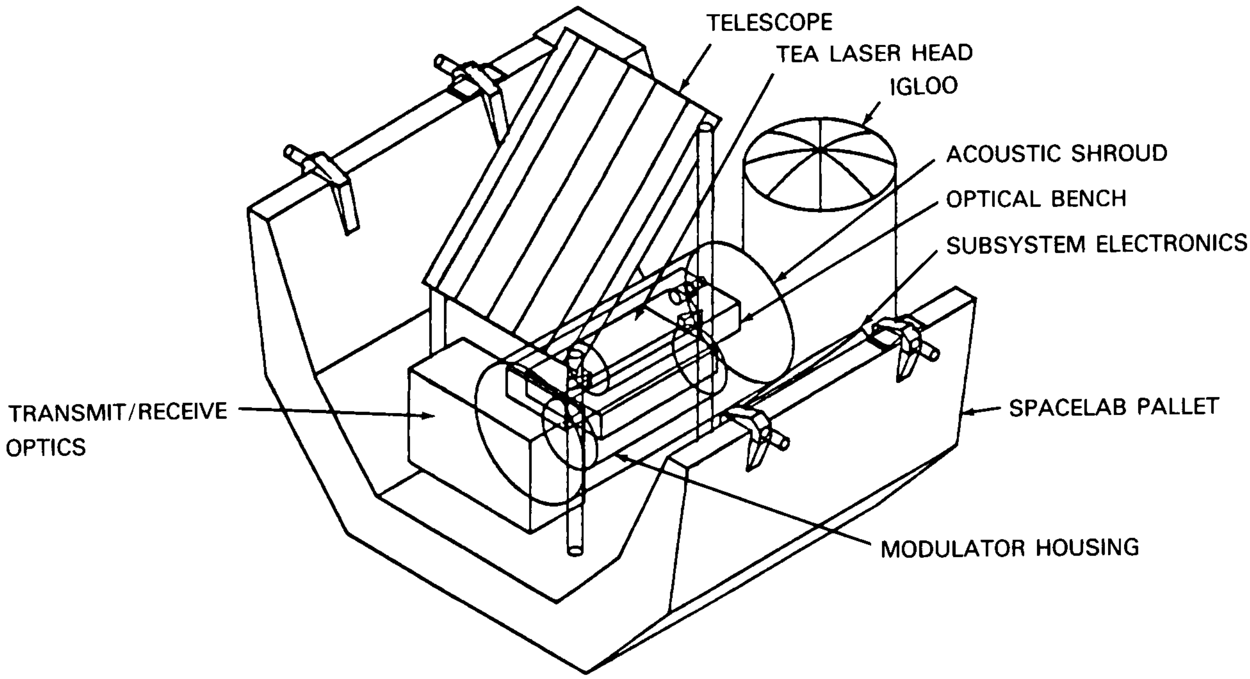


Figure C.5. SCALE configuration.

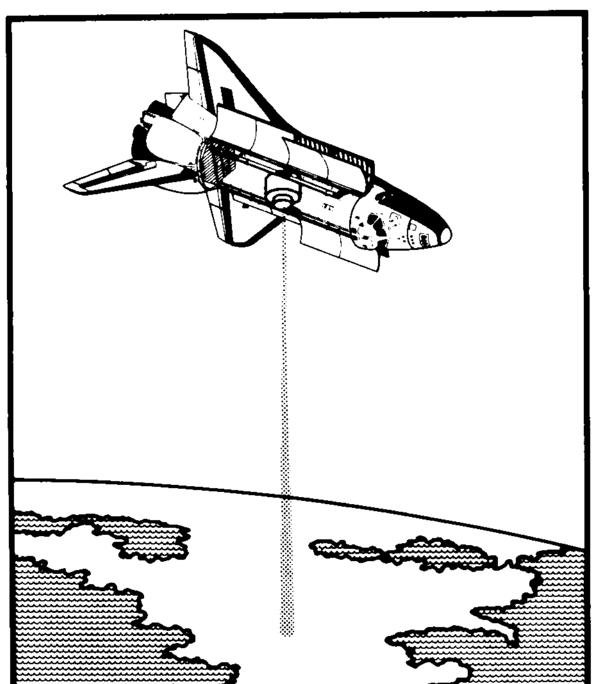


Figure C.6. SCALE scan pattern.

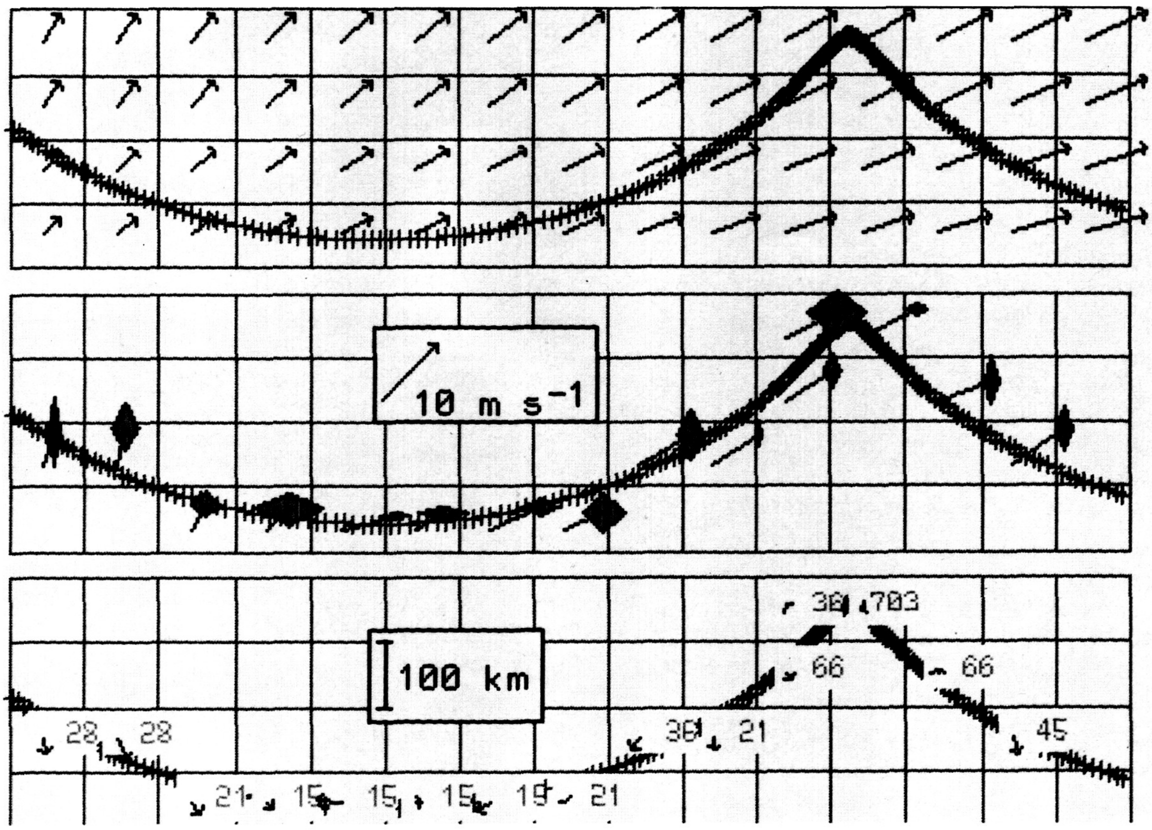


Figure C.7. Simulation of a Shuttle-based, fixed-beam Doppler lidar wind profiler. Scanning is achieved by pointing the lidar 40° from nadir and rotating the orbiter at 2 s^{-1}. The lidar is pulsed at 1 Hz. The top panel is the lidar shot pattern overlaid on a divergent wind field (DIV = 4.0 × 10^{-6} s^{-1}) with wind vectors spaced at 100 km. The middle panel shows the resulting wind vectors as interpreted by the lidar with "errorheads" used to display the standard deviations in the estimates of the u and v components. The bottom panel shows the number of shot pairs used in computing each wind vector and the vector differences between the input and output winds. Note, the smallest errors are in the grid containing the cusp and 703 shots.

ORIGINAL PAGE
COLOR PHOTOGRAPH

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